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MASTER

Potential Impacts of Brayton- and Stirling-Cycle Engines

R. C. Heft

November 15, 1980

Prepared for
U.S. Department of Energy
Through an agreement with
National Aeronautics and Space Administration
by
Jet Propulsion Laboratory
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DISCLAIMER

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ABSTRACT

Two engine technologies (Brayton cycle and Stirling cycle) currently being pursued by the U.S. Department of Energy have to be examined for their potential impacts if they achieved commercial viability.

An economic analysis of the expected response of buyers to the attributes of the alternative engines was performed. Hedonic coefficients for vehicle fuel efficiency, performance and size were estimated for domestic cars based upon historical data. The marketplace value of the fuel efficiency enhancement provided by Brayton or Stirling engines was estimated.

The effect upon various economic sectors of a large scale change-over from conventional to alternate engines was estimated using an economic input-output analysis. Primary effects were found in fuels refining, non-ferroalloy ores and ferroalloy smelting. Secondary effects were found in mining, transport, and capital financing.

Under the assumptions of 10 years for plant conversions and 1990 and 1995 as the introduction date for turbine and Stirling engines respectively, the comparative fuel savings and present value of the future savings in fuel costs were estimated.

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SECTION 1

SUMMARY

1.1 OVERVIEW

This report documents analysis of the potential impacts of the production and use of automotive Brayton and Stirling cycle engines. It was conducted as part of the Vehicle Systems Project by the Jet Propulsion Laboratory, California Institute of Technology, for the U.S. Department of Energy, Division of Transportation Energy Conservation.

The impacts of, or the associated barriers to, the adoption of engines other than the conventional Otto or Diesel cycle engines can be approximately categorized into three areas. The first are impacts resulting from the use of a vehicle with such alternate engines. Such impacts include traffic flows, road safety, fuel utilization, and requirements placed upon the automotive system infrastructure. The second category of impacts results from the manufacture of engines directly. These impacts result from the change of the factors of production for engine manufacture. The areas of impact include materials, labor, capital, and manufacturing energy use. The third major area of potential impacts is that of cost. For such engines to be adopted, the cost the user is willing to incur in the purchase and use of such vehicles must be commensurate with the cost the manufacturer is willing to incur to produce such vehicles for purchase. Brayton and Stirling engine vehicles are expected to provide a different set of attributes, principally in the area of improved fuel utilization, from that found in conventional vehicles. Accompanying this enhancement of fuel efficiency is expected to be higher manufacturing cost for the engines.

If the Brayton or the Stirling engine replaced the conventional engine in any substantial numbers, the replacement will take place in the context of a competitive marketplace. This direct competition between firms and between technologies circumscribes the arena of impacts. For the conversion from conventional to alternative engines to be substantial, all of the attributes of the alternate engine powered vehicle must fall within the realm of minimum market acceptability and at least one of the attributes must be clearly superior to that associated with the conventional engine.

This implies that the principal concerns can be reduced to three areas: First, the tradeoff between those attributes which are expected to differ most markedly from conventional automobiles, specifically cost and fuel efficiency; secondly, the sectorial, inter-sectorial and regional impacts of manufacturing these engines; and thirdly, the most significant impact associated with use of such engines, fuel utilization.

From these considerations, it was decided to focus the examination of the impacts and barriers associated with the advanced engines on three operative questions. Associated with the first area of impacts, the operative question was: How large are the potential petroleum displacement or conservation benefits of these engines in the period to 2010? Associated with the second area of potential impacts, the operative question was defined as: Would the production of such engines disrupt some economic sector of the economy, some region of the country, or place a significant demand upon a resource not readily available? The operative question associated with a third area of potential impacts was defined as: Does the higher expected fuel economy of advanced engines vehicles have a value to purchasers sufficient to offset the higher expected cost of production?

1.2 SECTORIAL and REGIONAL IMPACTS OF ADVANCED ENGINE PRODUCTION

An analysis of the possible economic impact resulting from the production of Brayton and Stirling cycle engines was performed at Argonne National Laboratories by Lawrence Hill with assistance from Daniel Santini and Eric Stenhejem. The DOE TECNET model, an impact analysis system based on a 185 sector, variable coefficient input/output model was a method used to analyze the economic impacts of the potential production of alternate engines. The study concluded that the commercialization of Brayton and Stirling engines would primarily impact the materials and petroleum sectors with possible but much smaller impacts in the transportation sectors, employment and capital. Since TECNET does not have a structural ceramic sector, the impacts of ceramic alternate engines could not be directly analyzed.

The most significant problem areas were found in the metals sector. The aluminum requirement of the Stirling engine combined with limited bauxite reserves could present a significant barrier to its commercialization.

Additionally, the electricity requirement for aluminum production could present localized barriers to the commercialization of such engines. If ceramic technology is not successful in the structural high temperature portions of either engine, the high cobalt content of the requisite casting alloys used could cause cobalt demand to double. The lack of assurance of a large quantity of cobalt available over the financial lifetime of an engine plant could provide a serious barrier to the production of such engines. The other material impacts were not judged as significant if economically efficient technologies for the recovery of known reserves could be developed. The year 2000 impacts are summarized in Table 1.1

Table 1.1 Year 2000 Impacts Summary

	Sector	Percent Change from Baseline Brayton	Stirling
Petroleum Sectors	Petroleum Refining Output	-17.3	-17.8
	Petroleum Refining Employment	-15.8	-16.2
	Petroleum Refining Capital Investment	-16.1	-16.6
	Petroleum Production	-54.6	-55.7
	Petroleum Production Employment	-54.6	-55.7
	Petroleum Production Capital Investment	-19.4	-19.0
	Pipeline Production	-29.2	-29.6
	Water Transport	- 5.4	- 5.2
Metals Sectors	Aluminum	4.0	20.9
	Nickel	12.7	9.6
	Cobalt	150.2	83.2
	Tungsten	24.7	11.3
	Chromium	3.4	8.5
	Bauxite	negligible	196.0
	Non-Ferrous Capital Investment	-	11.0%

1.3 ECONOMETRIC ANALYSIS OF VEHICLE ATTRIBUTES FOR ADVANCED ENGINES

A preliminary examination of the viability of advanced engines in a marketplace of purchasers with desires for quality, fuel economy, and performance and producers with cost and regulatory constraints was examined by Michael Block and Fred Nold of the Hoover Institution, Stanford University. A qualitative introduction on how vehicle attributes are determined in a marketplace was provided by JPL.

A sample of 401 different vehicles spanning the four years from 1975 through 1978 was stratified into three vehicle size categories. An econometric analysis was performed to determine the relationship between the price the vehicle commanded in the marketplace and the attributes of performance, quality, and fuel efficiency. The surrogate variables used for these attributes were brake horsepower per vehicle weight, weight, and EPA urban gas mileage. It was determined that for the data base in question, one more city mpg was worth approximately $74.00 in the marketplace. No statistically significant distinction in the value was found between the three vehicle size categories. An increase of 1/1000th in the horspower to weight ratio (approximately 1/2 second improvement in 0 to 60 time) was found to vary between approximately $95.00 and $25.00 depending upon the size of the vehicle.

1.4 FUEL CONSUMPTION IMPACTS

The analysis of the fuel consumption impacts of the advanced engines was performed at the Jet Propulsion Laboratory. Brayton and Stirling engines were substituted in new car sales for the conventional Otto cycle engine and the resultant fuel consumption impact against the all Otto cycle baseline was computed. A 10-year introduction was assumed starting in 1990 and reaching a maximum penetration of 90% of sales for turbine engines. Stirling engines were assumed to be delayed 5 years beyond that of turbines. The time period under consideration extended to the year 2010. The expectations on fuel economy for the Brayton and Stirling engines were based upon previous JPL analysis. The initial calculations were performed with a computerized bookkeeping algorithm which was sensitive to rate of sales, scrappage, and use vs. age characteristics of the automotive fleet.

An improvement in maximum domestic corporate average fuel economy was found to range between 14% for the metallic Brayton engine to 34% for the ceramic Stirling. The amount of transportation energy saved over the conventional vehicle baseline was found to range from 0.83 and 1.62 quadrillion Btus per year. The present worth of the fuel saved to year 2010 was found to range between 17 billion dollars and approximately 36 billion dollars depending upon the engine technology. This is summarized in Table 1.2.

Table 1.2. Summary of Fuel Consumption Impacts

Engine	Maximum CAFE	Maximum Annual Energy Saving (in QUADS)	Present Worth of Fuel Saved (in Billion Dollars)
Otto	32.1	-	-
Metallic Brayton	36.7	0.83	20.1
Ceramic Brayton	40.2	1.21	36.3
Metallic Stirling	41.6	1.28	16.9
Ceramic Stirling	43.1	1.62	22.7

1.5 SUMMARY OF FINDINGS

In the area of inner sectorial and resource impacts:

(1) Indirect or cross impacts on various economic sectors are negligible. The economic effects of advanced engine production appear to propogate through direct economic channels and do not unexpectedly sum up to a major impact in some economic sector.

(2) If the ceramic research and development activities associated with turbine engines are successful, there should be no major resource barrier to the turbine. If not, the cobalt requirement in the hot rotating parts of the turbine engine could cause a significant barrier to production. Other metal sectors are affected by turbine engine production but the effect is not large.

(3) The same finding holds in regard to the current efforts to eliminate the use of cobalt in the hot parts of the Stirling engine. Additionally, the large quantity of aluminum used in the structural parts of the Stirling engine could cause a signficant barrier to production because of limitations on bauxite production.

In the area of the tradeoffs between fuel economy and vehicle costs:

(1) Historically, the purchasers of new cars are not willing to fully pay for the life cycle fuel savings in the purchase price of a vehicle.

(2) In 1995, an alternative engine vehicle which is 20% more fuel efficient than a conventional vehicle could be priced at $250 (1978 dollars) above the conventional vehicle.

In the area of fuel consumption impacts:

(1) Significant substitution of advanced engines over conventional Otto cycle engines could save between 1 and 2 quadrillion Btus of transportation energy annually in the United States.

(2) If produced in moderate quantities, any of the alternative engines would more than justify any foreseeable government R&D expenditures in terms of the value of the fuel conserved. If such engines achieved 90% substitution over conventional Otto cycle engines the present worth of the fuel saved is of the order of 20 to 30 billion dollars.

SECTION 2

POSSIBLE ECONOMIC IMPACTS OF ALTERNATE ENGINE PRODUCTION

2.1 SUMMARY

This section is concerned with the economic impacts of the potential production of Brayton and Stirling engines under a moderate economic growth scenario(a growth and consumption oriented society constrained by rates of technological innovation and resource development). Beginning with the assumption of only conventional Otto cycle engines until 1990, three scenarios were used: (1) a continued 100% utilization of the conventional Otto cycle engine through 2000, (2) a gradual penetration of the Brayton engine from 1990, reaching 100% in 1998, and (3) a gradual penetration of the Stirling engine from 1992 reaching 100% in 2000. The DOE TECNET model, an impact analysis system based on a 185 sector, variable coefficient input-output model, was the method used to analyze the economic impacts of the potential production of the alternative engines. The study concluded that the commercialization of mature Brayton or Stirling engines would primarily impact materials and petroleum sectors with possible, but much smaller, impacts in transportation sectors, employment and capital. Since TECNET does not have a structural ceramics sector it could not be used to analyze all of the impacts of the ceramic versions of the alternative engines. However, the study hypothesized such impacts would be similar to those of the metallic alternative engines.

Brayton or Stirling engines require alloys not used in conventional automotive engines. As a result, the study found that mature alternative engine commercialization would require significant increases in the mining and smelting of nickel, chromium, tungsten, and cobalt. The TECNET model is not sufficiently disaggregated to account for the individual increases in these ore requirements so their individual impacts were calculated outside the model. These external calculations projected that mature alternative engine commercialization would result in approximately a 20% increase in the consumption of nickel, an 83% (Stirling) to 150% (Brayton) increase in the consumption of cobalt, an 11% (Stirling) to 25% (Brayton) increase in the consumption of tungsten, and a 3% (Brayton) to 8% (Stirling) increase in chromium. At present, the U.S. does not have large, economically recoverable reserves of any of these ores. Thus, the commercialization of mature alternative engines could result in a heavy dependence on imports for these metals. Alternatively, development of economically feasible recovery techniques for known U.S. deposits could significantly impact the localities of these deposits. That is, the national impact could be small, but the regional impact could be very large. The increased ferroalloys requirements due to the production of mature alternative engines would also have an impact on the smelting of these ores, since the number of domestic smelters is relatively small. However, as these smelters are generally located in urbanized areas, sufficient labor pools should exist to handle the increased manpower requirements.

The mature Stirling engine is expected to require significantly more aluminum (199 lbs) than the equivalent internal combustion engine (20 lbs) or Brayton engine (2 lbs). Hence, the study found that commercialization of the mature Stirling engine would increase aluminum consumption by 20% in 2000. This increase in aluminum requirements would significantly impact bauxite mining since it would require a doubling of bauxite production/importation in the period from 1990 to 2000. Also, as known bauxite reserves are expected to last only until 2000 at current production rate, and since the U.S. has bauxite reserves equivalent to only two or three years consumption, the significance of this impact is further increased. The increase in aluminum requirements of the mature Stirling engine would also impact aluminum production. However, since aluminum production is carried out in only two areas in the U.S. the impacts would be localized. An important impact of the increased aluminum requirement of the mature Stirling engine, addressed only peripherally by this study, is its energy impact. Aluminum production is electricity-intensive. Thus, increases in aluminum requirements could have a significant impact on the demand for electricity in those areas where aluminum production takes place.

Successful Brayton and Stirling engines would provide significantly better gas mileage than the conventional Otto cycle engine and, therefore, would impact petroleum refining which would, in turn, impact crude petroleum output. The study projects that the commercialization of either mature alternative engines would result in a decline of about 55% in crude petroleum output, and a decline of about 17% in petroleum refining. As a result, employment in the petroleum sectors would be expected to decline. Since alternative engines may use non-petroleum based fuels not currently marketed, investment in the production and marketing of the new fuels at the same time as petro fuel sales are declining could cause a capital squeeze. As a result of the declining fuel usage, capital investment declines were predicted in the production and refining sectors. Finally, as crude output and refining decrease, output of the pipeline and water transportation sectors would be expected to decline. It should be noted that such effects would be expected for any effective petroleum conservation activity.

Due to its level of aggregation (lack of structural ceramics sectors), the TECNET model was unable to analyze the impacts of the production of the ceramic Brayton and Stirling engines. Because the projected ceramic technology requires primary metal consumption of lithium, aluminum and magnesium, impacts could be expected in the respective mining sectors. Since advanced alternative engines are expected to have even greater fuel efficiency than the mature versions, they are projected to have similar, but larger, impacts in the petroleum sectors with the resulting impacts in capital, employment and transportation.

The above impacts could cause barriers to the commercialization of alternative engines. The most significant problem areas found were in the metals sector. The aluminum requirements of the mature Stirling engine and the limited bauxite reserves could present a significant barrier to its commercialization. Also, the electricity requirement of aluminum production could present localized barriers to the commercialization of the mature Stirling engine. Because of the high cobalt content of the casting alloys used, the cobalt demand was projected to double. Lack of assurance of this quantity of cobalt over the financial lifetime of an engine plant could also present a serious barrier to production. Other material impacts were not judged significant barriers if economically efficient technologies for the recovery of known reserves could be developed.

Table 2.1. Year 2000 Impacts Summary

	Sector	Percent Change from Baseline Brayton	Percent Change from Baseline Stirling
Petroleum Sectors	Petroelum Refining Output	-17.3	-17.8
	Petroleum Refining Employment	-15.8	-16.2
	Petroleum Refining Capital Investment	-16.1	-16.6
	Petroleum Production	-54.6	-55.7
	Petroleum Production Employment	-54.6	-55.7
	Petroleum Production Capital Investment	-19.4	-19.0
	Pipeline Production	-29.2	-29.6
	Water Transport	- 5.4	- 5.2
Metals Sectors	Aluminum	4.0	20.9
	Nickel	12.7	9.6
	Cobalt	150.2	83.2
	Tungsten	24.7	11.3
	Chromium	3.4	8.5
	Bauxite	negligible	196.0
	Non-Ferrous Capital Investment	-	11.0%

2.2 ALTERNATIVE ENGINE IMPACTS UNDER MODERATE ECONOMIC GROWTH

2.2.1 Introduction

This chapter examines the moderate economic growth scenario results obtained from TECNET and additional calculations external to TECNET. These additional calculations are necessary to fill the gaps left in TECNET results, due to the aggregation within the TECNET sectors. The results are presented for the baseline Otto cycle scenario (ARGON I), and the Brayton (ARGON II) and Stirling (ARGON III) alternatives. Socioeconomic impacts comparisons of the alternative engines to the conventional are examined. Socioeconomic impacts are disaggregated into primary and secondary impacts. Primary impacts are defined as those which result directly (i.e., as a result of direct production linkage) from the introduction of alternative heat engines. Secondary impacts result from changes in sectors indirectly linked to the alternative heat engines. For example, a primary impact may be a petroleum refining output reduction. This impact reduces crude oil production, water transportation demand, and the capital financing which would have been used to produce the lost petroleum refining output. The latter effects are secondary impacts. Figure 2.1 illustrates this relation. The primary impact section is divided into two units: Mature Brayton free turbine/Stirling engine materials impacts, and Mature Brayton free turbine/Stirling engine fuel impacts. Section 2.2.3 of this chapter explores secondary impacts.

TECNET, as currently constructed, can only analyze metallic-based alternative heat engines. Ceramic-based advanced engine impacts estimation requires significant noncomputerized research. This study's findings indicate the primary impacts of the alternative heat engines occur only in the materials and petroleum areas as a result of input substitutions. They also indicate that constraints to successful commercialization of alternative heat engines may occur as a result of secondary impacts. Environmental considerations may constrain the primary impacted smelting sector, but labor force and other economic constraints do not appear significant since smelters are located in urbanized areas and materials input supply patterns will not change significantly. Therefore, more detailed analysis has been conducted in the secondarily impacted sectors.

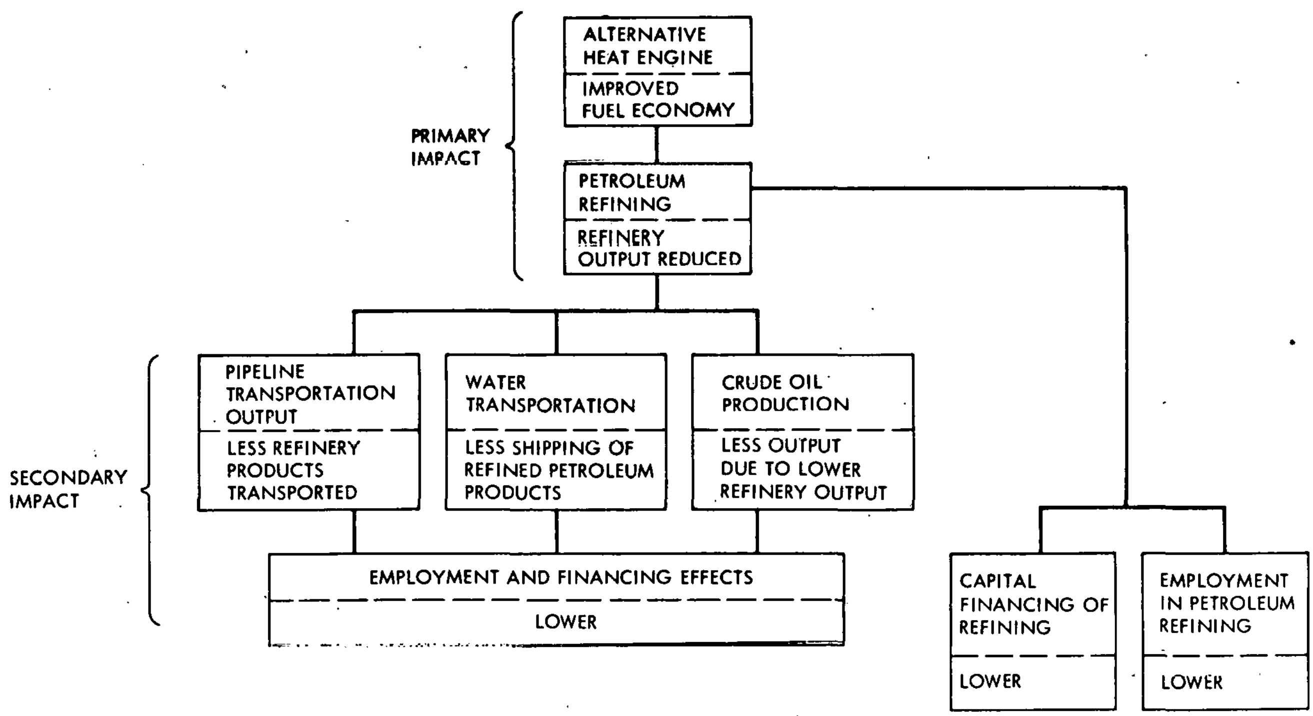

Figure 2.1. Primary and Secondary Impacts

2.2.2 Primary Socioeconomic Impacts

Should We Have a New Engine? (Reference 1) and the recently released Status and Projections of Automotive Technology 1978 (Reference 7) express concern about possible materials and petroleum related impacts since these effects may cause barriers to Brayton and Stirling engine production. Both publications devote chapters to fuel-energy and resources (materials) requirements and supply. Not surprisingly, this research presented here also indicates these areas as possible concern to successful commercialization of the alternative heat engines.

2.2.2.1 Primary Mature Brayton/Stirling Materials Impacts

Our findings show primary impacts occur in ferroalloy smelting and aluminum production under both Brayton and Stirling scenarios.

2.2.2.1.1 Ferroalloy Smelters. A primary effect of Brayton/Stirling engine introduction is in the smelting of nickel, chromium, tungsten, and cobalt. Increases in these metals are required for the alternative heat engines. The number of domestic smelters of these materials is relatively small. For example, nickel is refined at the AMAX, Inc. refinery at Port Nickel, Louisiana and the Hanna Nickel Smelting Company plant at Riddle, Oregon (Reference 2). The only significant cobalt smelter is the previously mentioned AMAX, Inc. Louisiana plant, where it is smelted with nickel (Reference 4). There are 26 producers of chromium alloys and metal (Reference 6). The Union Carbide Corporation plant at Bishop, California and the AMAX Inc. plant at Leadville, Colorado are the only significant producers of tungsten products (Reference 5). All of these smelters are located in areas where expansion of their facilities could take place. Sufficient labor pools exist to supply the expanded manpower requirements of these smelters. Provision of smeltering capacity does not appear to be a significant barrier to the production of either the Brayton or Stirling engines. However, more significant potential commercialization barriers are posed by the expanded ore needs of these refineries. These secondary impacts will be discussed extensively later in this chapter.

2.2.2.1.2 Stirling Aluminum Impacts. A mature 150 hp Stirling engine requires significantly more aluminum (199 lbs) than the equivalent Otto engine (20 lbs) or Brayton (2 lbs). The analysis of TECNET results confirms the expected primary impact on the aluminum sector. Table 2.2 summarizes the aluminum sector results of all three moderate economic growth scenario runs. Note that absolute aluminum production is expected to increase under all three scenario runs, but an egregious increase occurs with the introduction of the Stirling engine (ARGON III). The effect is illustrated by comparison of the scenarios. The introduction of the Stirling engine causes a 10.81% increase in aluminum output (Sector 87) by 1995 over an all ICE market (ARGON I). This increase accelerates to 20.93% by 2000. Comparing Brayton (ARGON II) and Stirling (ARGON III) scenarios, the Stirling-induced aluminum sector changes are even more conspicuous. The 1995 (2000) Stirling engines scenario requires 13.60% (26.00%) more aluminum output than the Brayton engines. These results are consistent with those expected, in view of the significant aluminum requirements for a Stirling engine.

This primary impact on aluminum may cause a significant barrier to penetration since the aluminum industry is very energy intensive and geographically concentrated in the Pacific Northwest and southern parts of the U.S. The Pacific Northwest is of particular concern since power shortages are possible for the aluminum industry before the time of potential introduction of the Stirling engine. Based on projected supply and demand for electric power in the region, the Bonneville Power Administration announced, in 1976, that it may not renew its power contracts with the Pacific Northwest aluminum industry after the 1984-88 period when the present contracts expire (Reference 8).

2.2.2.2 Primary Mature Brayton/Stirling Petroleum Impacts

There is general agreement that the Stirling and Brayton free-turbine engines will produce better mpg (lower fuel consumption) (References 1,7). For this analysis, the TECNET baseline mpgs were used. They are summarized in Table 2.3. It should be noted that TECNET calculates mpg on an arithmetic mean for small, medium, and large cars. TECNET does not allow for Brayton or Stirling light truck engines. TECNET mpgs were derived by assuming ICE

Table 2.2. TECNET Aluminum Sector Changes

	Absolute Amounts ($\$10^6$ 1977 dollars)				Annual Growth Rate (%)		
	1971	1977	1985	2000	1971-2000	1977-2000	1985-2000
ARGON I (all OTTO)	9,978	13,075	20,940	33,507	4.27	4.18	3.18
ARGON II (Brayton introduction in 1990)	9,978	13,075	20,957	32,160	4.12	3.99	2.90
ARGON III (Stirling introduction in 1992)	9,978	13,075	20,957	40,521	4.95	5.04	4.49

Table 2.3. TECNET MPG Assumptions

Year	Urban/Hiway	OTTO Small	OTTO Medium	OTTO Large	Brayton Small	Brayton Medium	Brayton Large	Stirling Small	Stirling Medium	Stirling Large
1977	Urban	23.1	18.2	12.9	7.0	5.8	4.5	8.2	6.7	4.9
	Hiway	33.6	25.6	18.4	10.3	8.5	6.6	11.5	9.4	7.3
1980	Urban	26.0	20.0	14.2	17.5	14.5	11.2	20.6	16.6	12.3
	Hiway	38.4	29.0	20.7	25.8	21.3	16.6	28.6	23.5	18.2
1985	Urban	30.9	23.2	16.3	35.0	29.0	22.3	41.1	33.3	24.7
	Hiway	46.5	34.7	24.5	51.6	42.5	33.1	57.3	47.0	36.4
1990	Urban	30.9	23.2	16.3	36.5	30.3	23.3	41.8	33.9	25.1
	Hiway	46.5	34.7	24.5	53.8	44.3	34.5	58.3	47.8	37.0
1995	Urban	30.9	23.2	15.3	38.1	31.6	24.3	42.4	34.4	25.5
	Hiway	46.5	34.7	24.5	56.0	46.1	35.9	59.3	48.5	37.6
2000	Urban	30.9	23.2	16.3	39.6	32.9	25.3	43.1	35.0	25.9
	Hiway	46.5	34.7	24.5	58.2	47.9	37.3	60.3	49.3	38.2

compliance with the interpretation of a 1985 arithmetic mean fleet mpg of 27.5. The Brayton/Stirling engine mpg estimates obtained from Should We Have a New Engine? were adjusted relative to the ICE figures. The same proportional difference between the ICE and alternative heat engine mpgs was maintained. Unfortunately, this methodology is biased toward higher fuel consumption than U.S. standards will imply, since U.S. standards (Energy Policy and Conservation Act, Public Law 94-163) are based on the harmonic mean. That is, average fuel economy is calculated by dividing the total number of passenger automobiles manufactured by a sum of terms, each of which is a fraction. The fractions are created by dividing the number of passenger automobiles of a given model type by the fuel economy measured by each type (Reference 10). Thus, the harmonic mean measures fuel consumption, not fuel economy (measured by the arithmetic mean). Budget constraints limited the analysis to the TECNET prescribed mpg assumptions, since changing them would have required re-coding of major portions of TECNET.

Table 2.4 summarizes the absolute TECNET derived impacts on petroleum refining output sector. However, had the harmonic mean been used to estimate fleet gallons per mile, lesser petroleum impacts would have resulted. With commercial production of the Brayton engine (ARGON II), sizable reductions in refining output occur in comparison with the all-Otto cycle (ARGON I) scenario. There is a 10.33% decline in refining production when ARGON II is compared to ARGON I in 1995. This escalates to a 17.32% reduction by 2000. The Stirling engine (ARGON III) produces the same dramatic results when compared with an all-Otto cycle output (ARGON I). There is a 10.36% decline by 1995 and a 17.79% decline by 2000.

2.2.2.3 Preliminary Primary Advanced Engine Impacts

Advanced alternative heat engines require materials that exhibit mechanical, dimensional, and chemical stability, coupled with long life at high operating temperature. Since mature engine metallic components are limited to maximum temperatures of 1200-1400° F (649-760° C), efforts have been directed toward the development of ceramic or "glass ceramic" materials which can operate hundreds of degrees above metallic materials. Glass ceramics are materials that can be formed into appropriate configurations as an amorphous glass material and then transformed into a polycrystalline

Table 2.4. TECNET Petroleum Refining Output

Scenario \ Year	Absolute Changes				Annual Growth Rates (%)		
	1971	1977	1985	2000	1971-2000	1977-2000	1985-2000
ARGON I (all OTTO)	42,656	48,180	55,532	81,439	2.25	2.31	2.59
ARGON II (Brayton begins 1990)	42,656	48,180	55,533	67,333	1.59	1.47	1.29
ARGON III (Stirling begins 1992)	42,656	48,180	55,533	66,953	1.57	1.44	1.25

ceramic during controlled firing (Reference 7). These ceramic materials will most likely have lithium aluminum silicate, aluminum silicate, or magnesium-aluminum silicate bases. Thus, primary impacts on the ceramics industry can be expected. TECNET is unable, due to its level of aggregation, to account for these primary impacts. Consequently, significant external calculations must be performed to ascertain whether ceramic technology posts a possible commercialization barrier.

2.2.3 Secondary Impacts

2.2.3.1 Materials Resource Requirements Impacts

Mature Brayton and Stirling engines require more stainless steel and introduce requirements for superalloys that are not utilized in present autos. The term superalloy was coined after World War II to describe a group of alloys developed for use in high temperature applications in superchargers and jet engines. These alloys possess relatively high tensile and creep strengths at temperatures normally found in jet engines (1800^{o} F or higher). A typical superalloy has the following chemical composition: 19.5% chromium, 13.5% cobalt, 4.3% molybdenum, .1% carbon, 1.3% aluminum, 3% titanium, .001% to .1% boron, 2% iron, and the balance about 56% nickel.[2] Other alloys use a large percentage of tungsten. Hardness at elevated temperatures is the most important property possessed by tungsten alloys. Heat and abrasion resistance, shock resistance, corrosion resistance, and high strength at elevated temperatures are other properties of tungsten- bearing steel alloys. As a result of these alloy characteristics, substantial amounts of cobalt, nickel, chromium, and tungsten will be required by the alternate engines (Reference 1).

Unfortunately, the TECNET system is not sufficiently disaggregated to account for the impacts on these ores. They are included in the iron ores sectors and compose a small percentage of this sector. As a result, calculations of the impacts of the Brayton and Stirling engines on these ores has to be conducted externally to the TECNET model. A methodology section will be followed by sections that describe the impact on each ore, assuming the previous penetration estimates (Section 2.2.2). Table 2.5 summarizes the required pounds of ore required per engine.

2.2.3.1.1 Methodology. To make this study compatible with the TECNET results, the TECNET car weight classes for small (1600-2610), medium (2610-3160), and large (3150-6000) were used. The Motor Vehicle Manufacturers' Association classification for light truck weights (4000-10,000) were also used (Reference 3). Probable average weights for each size class are listed in Table 2.6. They were obtained in consultation with JPL based on number of cars in each class. From the average weight, the horsepower was calculated based on the following formula:

$$hp/car = .03\ hp.lb * lb/car$$

The resultant horsepowers are also found in Table 2.6. Since the JPL report (Reference 7) cites only two horsepower classifications per Brayton and Stirling engine, separate calculations based on horsepower were used to arrive at the pounds per ferroalloy per auto for the three classes of auto used in this study. This was done using the following formula, which is based on an assumption of a direct linear relationship with the nearest horsepower classification:

$$APO_{i,j,k} = \frac{AHP_{i,j}}{JHP_{i,n}} * JPO_{i,n,k}$$

where:

i = engine type,

j = ANL car classification,

k = ore type, and

n = JPL car classification

where:

$APO_{i,j,k}$ = ANL estimate of pounds per car of ferroalloy ore k for engine type i in car classification j,

$AHP_{i,j}$ = ANL estimate of horsepower for engine type i in ANL car classification j,

$JHP_{i,n}$ = JPL estimate of horsepower for engine type i in JPL car classification n, and

$JPO_{i,n,k}$ = JPL estimate of pounds per car of ferroalloy ore k in JPL car classification n for engine type i.

Table 2.7 summarizes the results of these calculations. It was assumed the ore content per unit did not vary per ICE class car.

Table 2.5. Metal Requirements for Alternate Engines

Metal[a]	Engine Type					
	Pre-Catalyst OTTO	1975 Catalyst OTTO	1970 hp Stirling	119 hp Stirling	150 hp Free-Turbine Brayton	105 hp Free-Turbine Brayton
Chromium	8.0	10.8	24.6	19.2	14.5	12.1
Nickel	4.5	4.5	10.8	8.5	11.5	8.9
Cobalt	0	0	2.2	1.5	3.9	2.7
Tungsten	0	0	0.37	0.26	0.8	0.56

[a]All ores are in pounds per engine

Table 2.6. Salient Characteristics of Each Class of Car

Vehicle Class	Salient Characteristics		
	Weight Range	Average Weight	Horsepower
Small	1,610 to 2,610	2,500	75
Medium	2,610 to 3,160	3,000	90
Large	3,160 to 6,000	5,000	150
Light Truck	4,000 to 10,000	8,000	240

Table 2.7. Estimated Pounds of Ore per Auto Unit

Ore Type	Engine Type and Car Classification								
	Brayton			Stirling				OTTO	
	Medium 90 hp	Large 150 hp	Light Truck 240 hp	Small 75 hp	Medium 90 hp	Large 150 hp	Light Truck 240 hp	Pre-Catalyst to 1974	Catalyst 1975
Chromium	10.37	14.5	23.2	12.1	14.5	21.7	34.73	8.0	10.8
Cobalt	2.31	3.9	6.2	0.95	1.13	1.94	3.11	0	0
Tungsten	0.48	0.8	1.28	0.15	0.20	0.33	0.52	0	0
Nickel	7.63	11.5	13.4	5.36	6.42	9.53	15.25	4.5	4.5

2.2.3.1.2 Nickel Impacts. Nickel's greatest value is in alloys with other elements, where it adds strength and corrosion resistance over a wide range of temperatures. U.S. proven reserves of nickel are small and concentrated in relatively few areas; however, the country possesses large potential resources that could be used if technological and environmental problems are resolved. Since reserves are small and spatially concentrated, the impact of Brayton and Stirling engines would be most noticeable in these nickel mining areas.

A simple multiplication and summation of the number of cars and the per pound weight of nickel per car was used to determine total car consumption of nickel. Table 2.8 summarizes these results for each engine type in the year 2000 and compares it with 1970 figures. Car sales in the year 2000 were assumed to be 13.5 million units, divided among 25% small, 25% medium, and 50% large cars. Light truck sales were assumed to grow at a 4% compound rate, which is approximately four times faster than assumed car sales. This accounts for recent trends in van/pickup sales, but assumes a slower grotwh rate than occured in the past seven years. The total pounds of nickel consumed were converted to thousands of short tons (2000 pounds per short ton). Total U.S. consumption of nickel (exclusive of scrap) in 1970 was 155,719 short tons. This means that automotive nickel (ICE) in 1970 was approximately 14% of the U.S. total. Assuming an all-ICE market in 2000 and using the Bureau of Mines year 2000 projection of 415,000 short tons, the percent nickel consumed by the auto industry drops to 9.5%. This is consistent with the Bureau of Mines projections (Reference 1).

If the Brayton engine is produced under the moderate growth scenario, there is a projected increase in nickel consumption of 23.3%. The Stirling engine would result in a more moderate increase of 20%. Thus, the introduction of the Brayton of Stirling engines will double the expected nickel consumption by the auto industry. This will have significant impacts on certain localities in the U.S. At present, the only significant U.S. producer is the Hanna Mining Co., which operates an open pit mine and ferro-nickel smelter at Riddle, Oregon. The Hanna Mining Company mine, opened in 1954, annually produces about 13,000 short tons of nickel. The only other nickel smelters in the U.S. are the AMAX Nickel Division of American Metal

Table 2.8. Nickel Ore Consumed by Auto

Year	Engine Type			
	OTTO 1970	OTTO 2000	Brayton 2000	Stirling 2000
Small Cars				
number of units	1,428,850	3,375,000	3,375,000	3,375,000
lbs/unit	4.5	4.5	4.5	5.36
total lbs	6,429,825	15,187,500	15,187,500	18,090,000
total short tons, 10^3	3.214	7.594	7.594	9.045
Medium				
number of units	3,395,620	3,375,000	3,375,000	3,375,000
lbs/unit	4.5	4.5	7.63	6.42
total lbs	15,280,290	15,187,500	25,751,250	21,667,500
total short tons, 10^3	7.640	7.594	12.876	10.834
Large				
number of units	3,580,530	6,750,000	6,750,000	6,750,000
lbs/unit	4.5	4.5	11.5	9.53
total lbs	16,112,385	30,375,000	77,625,000	64,327,500
total short tons, 10^3	8.056	15.188	38.813	32.164
Light Trucks				
number of units	1,256,260	4,075,500	4,075,500	4,075,500
lbs/unit	4.5	4.5	18.4	15.25
total lbs	5,653,170	18,337,500	74,989,200	62,143,750
total short tons, 10^3	2.827	9.169	37.495	31.072
Total short tons, 10^3	21.738	39.545	96.778	83.115

Climax, Inc., a nickel-copper refinery at Port Nickel, Louisiana, and the Huntington, West Virginia integrated rolling mill owned by International Nickel Co., of Canada (INCO).

It should be noted that scrap is a currently significant source of nickel supply. Nickel scrap is made in forming and shaping operations in primary processing plants, equivalent to the material considered as home scrap in steel mills. Nickel scrap is generated in fabricating plants that use nickel-bearing materials such as stainless steels and superalloys. In the U.S, high-nickel alloy scrap normally is not utilized unless its composition is known within close limits so that it can be reused as is. Otherwise, it usually is exported to Japan or the Federal Republic of Germany where it is processed to separate the contained elements in a form suitable for reuse. As the Brayton and/or Stirling are introduced, this practice might be curtailed and domestic reuse of nickel scrap increased.

2.2.3.1.3 Cobalt. Table 2.9 summarized the cobalt consumption by baseline and alternative engine scenarios. The figures were obtained by the same process used in nickel computations. Cobalt, a little-known but strategic metal, has been developed through the centuries from an obscure coloring additive into an essential element in many alloys and an important ingredient in chemical compounds. In most of its alloying applications, cobalt imparts essential qualities such as heat resistance, high strength, wear resistance, and superior magnetic properties. The basic U.S. problem regarding cobalt is excessive dependence (98%) on foreign sources of supply, combined with concentration of the higher grade deposits in only a few areas of the world. For example, averaged over the period 1972 to 1975, cobalt consumption was 13.4 short tons with about 75% of U.S. imports originated in Zaire. Nineteen and seven tenths short tons is projected as most probable comsumption in 2000. There was no consumption of cobalt by the automotive industry in 1970 and this would not change if the baseline ICE scenario were followed to 2000.

Drastic changes would result if the Brayton or Stirling engines were introduced. If the Brayton scenario were introduced, the automotive consumption would be 150.7% of the currently projected U.S. demand. If the

Table 2.9. Cobalt Consumed by Auto

Year	Engine Type			
	OTTO 1970	OTTO 2000	Brayton 2000	Stirling 2000
Number of SMALL Cars	1,428,850	3,375,000	3,375,000	3,375,000
Lb/units	0	0	0	0.95
Total lbs	0	0	0	3,206,250
Total short tons, 10^3	0	0	0	1.603
Number of MEDIUM Cars	3,395,620	3,375,000	3,375,000	3,375,000
Lb/units	0	0	2.31	1.13
Total lbs	0	0	7,796,250	3,813,750
Total short tons, 10^3	0	0	3.898	1.907
Number of LARGE Cars	3,580,530	6,750,000	6,750,000	6,750,000
Lb/units	0	0	3.9	1.94
Total lbs	0	0	26,325,000	13,095,000
Total short tons, 10^3	0	0	13.163	6.548
Number of LIGHT Trucks	1,256,260	4,075,000	4,075,000	4,075,000
Lb/units	0	0	6.2	3.11
Total lbs	0	0	25,265,000	12,673,250
Total short tons, 10^3	0	0	12.633	6.337
Total short tons, 10^3, for all sizes	0	0	29.694	16.395

Stirling scenario were introduced, the increase in use would be 83.2% of probable U.S. demand. This could imply unacceptable dependence of the auto industry on foreign sources of cobalt supply. Increased domestic production would be desirable from a risk aversion point of view. Without increased domestic production, the highly centralized source of foreign supply would provide the producing countries with leverage whereby prices could be artificially increased or supplies decreased (or both) in a manner currently adopted by some countries that export raw materials. In the event of substantially increased domestic production, significant local impacts would occur in Ely, Minnesota, in the Duluth gabbro complex, and the Stillwater complex in Montana, where the Bureau of Mines indicates possible sources of cobalt exist. Another significant localized impact may occur on the west coast and Hawaii, where the mining of seabed nodules is a possibility. Additionally, increased smelting may result in significant impacts to the Braithwaite, Louisiana, area where AMAX, Inc. operates a nickel-cobalt refinery.

2.2.3.1.4 Tungsten. Tungsten applications are based on the extreme hardness and wear resistance of tungsten and its alloys and their ability to retain hardness and strength at elevated temperatures, on tungsten's favorable electrical and thermoionic properties, on its high melting point, and on its development as an important material in nuclear and space applications. Even without alternative engine usage, the unique, high temperature properties of tungsten suggest increased demand. Unless significant increases in tungsten reserves are developed by new extraction and processing techniques that will economically recover tungsten from low grade sources, future use of tungsten will be restricted and more expensive and less satisfactory substitutes employed (Reference 5).

Table 2.10 summarizes the tungsten consumption by baseline and alternative engine scenarios. The figures were obtained by the same process used in previous computations. The Bureau of Mines estimates that 24.7 thousand short tons will probably be demanded in 2000 without alternative engine usage. As a result of alternative engine usage, another 1.78 to 6.12 thousand short tons would be added to that demand estimate. Thus, a Brayton

Table 2.10: Tungsten Consumption by Auto Type

Year	Engine Type			
	OTTO 1970	OTTO 2000	Brayton 2000	Stirling 2000
Number of small cars	1,428,850	3,375,000	3,375,000	3,375,000
Lb/units	0	0	0	0.16
Total small car lbs	0	0	0	540,000
Total small car consumption, 10^3 short tons	0	0	0	0.27
Number of medium cars	3,395,620	3,375,000	3,375,000	3,375,000
Lb/units	0	0	0.48	0.20
Total medium car lbs	0	0	1,620,000	675,000
Total medium car consumption, 10^3 short tons	0	0	0.81	0.34
Number of large cars	3,580,000	6,750,000	6,750,000	6,750,000
Lb/units	0	0	0.80	0.33
Total large car lbs	0	0	5,400,000	2,227,500
Total large car consumption, 10^3 short tons	0	0	2.70	1.11
Number of vans/pickups	1,256,260	4,075,500	4,075,500	4,075,500
Lb/units	0	0	1.28	0.52
Total van/pickup lbs	0	0	5,216,640	2,119,260
Total van/pickup consumption, 10^3 short tons	0	0	2.60	1.06
Total short tons, 10^3, all sizes	0	0	6.11	2.78

engine production will result in a 24.8% increase in expected demand, and the Stirling engine will cause an 11.3% increase. The majority of the economic impact will be felt in Leadville, Colorado, and Bishop, California. This is because most of the domestic tungsten recovered was from facilities of the Pine Creek mine of Union Carbide Corporation near Bishop, California, and the American Metal Climax, Inc. (AMAX) mine near Leadville, Colorado. Both recovered tungsten as a co-product or by-product of molybdenum. Union Carbide, the largest U.S. tungsten producer, is vertically integrated and mines, recovers, processes, purifies, and consumes tungsten. In 1974 and 1975, four principal plants in the United States processed concentrate to ammonium paratungstate (APT) on a custom basis. These plants were located near Bishop, California, at Euclid, Ohio, at Towanda, Pennsylvania, and at Glen Cove, New York. Another place where significant economic impact may occur is the Searles Lake, California area. It is believed that 135 million pounds of contained tungsten are present in the brine solutions there. If an economical method of recovering this tungsten is developed, current domestic reserves might be increased by 50% to 60%. This possibility becomes more likely when considering the fact that at current production rates, U.S. reserves of tungsten will be exhausted by 2010.

2.2.3.1.5 Chromium. Chromium is one of modern industry's most versatile elements. It has a wide range of usage in three types of industries; metallurgical, chemical, and refractory. In addition, it is one of the nation's most important strategic and critical materials. Chromium is used in iron, steel and nonferrous alloys to enhance various physical properties, especially resistance to corrosion or oxidation. The use of chromium to produce stainless steel and in plating of metals are two of its more important applications. Its use in other applications such as alloy steels, nickel-chromium heating elements, pigments, leather processing, catalysts, and refractories is also important. There is no known substitute for chromium in stainless steel; stainless steel can be made without nickel but not without chromium.

Table 2.11 summarizes the chromium consumption by baseline and alternative engine scenarios. The figures were obtained by the same process used in previous computations. Primary chromium requirements of the United

Table 2.11. Chromium Consumption by Auto Type

Year	Engine Type: OTTO 1970	OTTO 2000	Brayton 2000	Stirling 2000
Number of Small Cars	1,428,850	3,375,000	3,375,000	3,375,000
Lb/units	8	10.8	10.8	12.1
Total small car lbs	11,430,800	36,450,000	36,450,000	40,837,500
Total small car consumption, 10^3 short tons	5.72	18.23	18.23	20.42
Number of Medium Cars	3,395,620	3,375,000	3,375,000	3,375,000
Lb/units	8	10.8	10.8[a]	14.5
Total medium car lbs	27,164,960	36,450,000	36,450,000	48,937,500
Total medium car consumption, 10^3 short tons	13.58	18.23	18.23	24.47
Number of Large Cars	3,580,000	6,750,000	6,750,000	6,750,000
Lb/units	8	10.8	14.5	21.7
Total large car lbs	28,640,000	72,900,000	97,875,000	14,647,500
Total large car consumption, 10^3 short tons	14.32	36.45	48.94	73.24
Number of light truck	1,256,260	4,075,500	4,075,500	4,075,500
Lb/units	8	10.8	23.2	34.73
Total light truck lbs	10,050,000	44,010,000	94,551,600	1,415,247,500
Total light truck consumption, 10^3 short tons	5.03	22.01	47.28	70.76
Total short tons, 10^3, all sizes	38.65	94.92	132.68	188.89

[a]Adjusted to compensate for lack of data specification.

States in 2000 are expected to range between 840 and 1280 thousand short tons. Bureau of Mines forecasts indicate that the most probable demand for primary chromium in 2000 will be 1.1 million short tons (Reference 6). In 1970, there were 500,000 short tons demanded in the U.S., of which 41,000 short tons were demanded by the auto industry (8.2%). The expected 2000 demand under the ICE scenario would be 94.92 thousand short tons, or 8.6% of the most probable U.S. demand. The Brayton scenario would require 132.68 thousand short tons or 12.1% of 200 most probable demand, while the Stirling would require 188.89 thousand short tons, or 17.2% of the expected demand. The Stirling engine penetration will nearly double the required automotive consumption of chromium in 2000. It can be expected that much of this impact would affect nonchemical domestic producers of chromium alloys and metal in the Midwest. Affected cities with these industries include: Calvert City, Kentucky; Beverly, Ohio; Steubenville, Ohio; Alloy, West Virginia; Marietta, Ohio; Maple Grove, Ohio; Louisville, Kentucky; Hammond, Indiana; Jackson, Ohio; and Columbiana, Ohio. Even bigger impacts could occur in the Stillwater complex in Montana where chromite exists, but is now uneconomical to extract. No chromium is domestically produced for domestic consumption at this time. On the whole, the chromium industry impacts caused by alternate engine production represent only a small proportion of the projected output of the industry. Further, the industry has a relatively large number of separate urban locations in declining economic areas where any increase in demand may result in positive impacts through job creation for unemployed workers.

2.2.3.1.6 Bauxite Impacts. A mature Stirling engine requires 199 pounds of aluminum per 150 hp. An equivalent Brayton engine requires two pounds of aluminum, while an ICE equivalent requires 20 pounds. As expected, this study shows the aluminum sector output to be primarily impacted by the Stirling commercialization scenario (ARGON III). Historically, the commercial production of primary aluminum has been based almost entirely on the use of bauxite, in which the aluminum occurs largely as hydrates of alumina (Reference 8). Thus, a significant secondary impact in bauxite mining was expected. TECNET aggregates the bauxite mining into the nonferri ore mining sector. Unfortunately, lead, zinc, mercury, and other nonferrous ores are also included in this sector. In 1975, lead composed 62.2% of the production value of all nonferrous alloys. Bauxite production value was only 2.5%. As a result, it would take a conspicuous increase in bauxite production to significantly change the nonferrous ore mining sector. TECNET analysis indicates this is exactly what happens. The 1995 ARGON III output of nonferrous ores increases 3.90% over the ARGON I (ICE) results, and in 2000 the increase is 7.59%. Since zinc (increases of .38% in 1995 and .95% in 2000) and lead (decreases of .001% in 1995 and .003% in 2000) refining show no significant changes, there is ample reason to believe the nonferrous ore changes result from the increases in Stirling engine induced bauxite mining. The following procedure was used to disaggregate the bauxite mining impact from other nonferrous ores.

First, the 1975 production value obtained for each ore was divided into total 1975 nonferrous ores production value. These figures were obtained from Commodity Data Summaries 1977 (Reference 9). They are summarized in Table 2.12. Second, the total nonferrous output for 1985 ARGON III (TECNET results) were multiplied by Step 1 results. This was done for four categories: zinc, lead, bauxite, and all other nonferrous ores. Table 2.13 reflects these results. Third, the zinc and lead ore mining was assumed to grow at the same annual rate of growth as zinc and lead refining. The zinc and lead ore results obtained in Step 2 were adjusted to 1990 and 2000 with these rates. The nonferrous ore growth rate was applied to that sector to obtain 1990 and 2000 total sectoral outputs (row 5 of Table 2.13). Fourth, the other nonferrous ores category was assumed to be the same constant percent of the total as it was in 1985 (35.3%). At this point, all the ore values except bauxite have been obtained for 1990 and 2000. These results are summarized in Table 2.13. Fifth, the lead, zinc, and other nonferrous categories were summed and subtracted from the total, yielding the bauxite results reflected in Table 2.13.

The results indicate a significant secondary impact of the Stirling engine commercialization in Bauxite mining. The introduction of this engine will require a 196% increase from 1990 to 2000 in production and/or importation of bauxite. This is a significant possible barrier to Stirling commercialization, since known world reserves of bauxite are adequate to meet work demand through 2000 at present production rates. This interval would be significantly shortened by mature Stirling engine production. Another problem is that bauxite reserves in the United States are equivalent to only two or

Table 2.12. Nonferrous Ores Statistics

	Production Value ($10) 1975	% of Total	
Lead	267.2	26.2%	
Zinc	366.1	36.0	
Bauxite	25.1	2.5	
Mercury	1.2	0.0	35.3% other*
Uranium	281.4	27.6	
Vanadium	49.3	4.8	
Titanium	26.9	2.6	
Tin	1.1[a]	0.0	
Total	1018.3	100%	

[a]Approximate value.

*Rounding accounts for differences.

Table 2.13. Bauxite Sector Output Estimates

	1985	% from Table 3.11	1990	2000
Lead	695.9	26.2	804.0	1073.2
Zinc	964.1	36.0	1053.0	1256.2
Bauxite	66.4	2.5	181.1	537.2
Other	937.5	35.3	1111.8	1563.8
Total	2656.0	100	3149.9	4430.4

three years' consumption. Low grade domestic bauxite resources are also inadequate to meet long-term demand (Reference 8).

Another expected secondary impact would be significant increases in capital investment to the nonferrous metals sector. TECNET results indicate a 7.19% (1995) to 10.99% (2000) increase in capital investment when the baseline ICE and Stirling scenarios are compared. This is exclusively a result of the projected increases in bauxite mining. Since the input-output table is not constrained by actual ore reserves, this is an expected TECNET output. In reality, the U.S. will have used up domestic supplies of bauxite ore long before the 1992 introduction of Stirling engines. Thus, the only way this impact will occur is if bauxite mining concerns purchase the needed equipment in the U.S.

2.2.3.1.7 Summary of Materials-Related Secondary Impacts. The impact of alternative engines on ferroalloys is extensive. Cobalt and chromium impacts appear to be negative. That is, the United States is totally dependent on importing these metals and increased consumption can only accentuate the monopolistic position of exporting countries. The negative impact of these metals could be offset by mining of seabed nodules. In the event of seabed mining, positive economic impacts should be felt on the west coast, particularly California. Nickel, bauxite, and tungsten resources exist in the U.S., but increased demand for them may exhaust domestic supplies by 2000.

2.2.3.1.8 Recent Developments. After the completion of the TECNET analysis of Brayton and Stirling engine production impacts, the Department of Energy contracted for conceptual designs of the next generation of Brayton cycle research engines.

The conceptual designs of two of these efforts, DDA-1AGTE from the Detroit Deisel Allison Division of General Motors and the FORD-1AGTE from the Ford Motor Company, have been examined to compare the content of the four critical metals in these new designs to the generic turbine analysis via TECNET.

The sales weighted material content of the turbine analyzed via TECNET in comparison to the two new designs is as follows*:

Table 2.14. Sales Weighted Material Content

Engine	Ni	Cr	Co	W
TECNET Turbine	7.87	4.75	4.18	0.86
DDA-1AGTE	6.17	5.52	0.06	0.24
FORD-1AGTE	1.96	5.02	3.40	0.34

*units of pounds not including scrap recovery

To the extent that these conceptual designs are representative of year 2000 production turbines in size and alloy used, the same assumptions used for the generic TECNET turbine yields the following changes in demand for the four metals:

Table 2.15. Percent Increase in Year 2000 Demand Due to to Alternative Engine Production

ENGINE	Ni	Cr	Co	W
TECNET Turbine	13.8	3.4	150.7	24.8
DDA-1AGTE	10.9	4.0	2.2	6.9
FORD-1AGTE	3.4	3.6	122.6	9.8

Effects of new designs:

Ni: The DDA concept still requires a modest increase while the FORD concept's 3.4% increase is probably not of concern.

Cr: No significant change but a 3% to 4% increase is unlikely to produce a significant barrier to production.

Co: The DDA concept removes Co as a concern, but the 122% increase for the FORD design remains a probable barrier.

W: Both designs reduce the increase in tungsten to less than 10% over projected baseline demand.

2.2.3.2 Secondary Petroleum Impacts

Earlier, it was noted that alternative heat engines primarily impacted the petroleum refining sector. This causes significant secondary impacts. Each secondary impact will be discussed separately. The commercialization of the relatively more efficient Brayton engine (ARGON II) compared to an all-ICE (ARGON I) market causes crude petroleum output to decline 29.14% in 1995 and 54.62% in 2000. The even more efficient Stirling engine (ARGON III) comparison with ICE (ARGON) indicates crude petroleum output declines 29.05% in 1995 and 55.70% in 2000. These results are not unexpected, since the mpg inputs for the Stirling and Brayton engines are significantly higher than those for the ICE. Table 2.16 summarizes these comparisons. As a result of the petroleum refining and crude production reductions, employment in these sectors was predicted to decline. This was borne out by the TECNET results. The crude petroleum and gas employment under the Stirling scenario was 29.05% less than the ICE scenario in 1995 and 55.70% less in 2000. This sector's employment fell 29.04% (1995) and 54.62% (2000) for Brayton/ICE comparisons. Employment in the petroleum refining sectors would also decline significantly from the ICE case when Brayton (9.44% in 1995 and 15.83% in 2000) or Stirling (9.46% in 1995 and 16.25% in 2000) engines are introduced.

2.2.3.3 Secondary Advanced Engine Impacts

Secondary advanced engine impacts can be expected to occur in the petroleum and mining sectors. The petroleum sector impacts are expected to be greater than those that occur for mature engines. Materials secondary impacts can be expected in bauxite, lithium, and magnesium ore mining because ceramic technology requires primary metal consumption of lithium, aluminum, and magnesium. While the bauxite results from the study of mature engines can be easily transferred to these engines, the lithium and magnesium demands require additional study similar to that previously done for the materials effects of mature engines.

Table 2.16. Summary of 1995 and 2000 MPG Comparisons

			1995	2000	% Difference for Equivalent Car 1995	% Difference for Equivalent Car 2000
OTTO	Urban	Small	30.9	30.9		
		Medium	23.2	23.2		
		Large	16.3	16.3		
	Hiway	Small	46.5	46.5		
		Medium	34.7	34.7		
		Large	24.5	24.5		
					Brayton/OTTO 1995	Brayton/OTTO 2000
Brayton	Urban	Small	38.1	39.6	23%	28%
		Medium	31.6	32.9	36%	42%
		Large	24.3	25.3	49%	55%
	Hiway	Small	56.0	58.2	20%	25%
		Medium	46.1	47.9	33%	38%
		Large	35.9	37.3	47%	52%
					Stirling/OTTO 1995	Stirling/OTTO 2000
Stirling	Urban	Small	42.4	43.1	37%	39%
		Medium	34.4	35.0	48%	48%
		Large	25.5	25.9	56%	56%
	Hiway	Small	59.3	60.3	28%	30%
		Medium	48.5	49.3	40%	42%
		Large	37.6	38.2	53%	58%

2.2.3.4 Sectors Not Impacted

Sectors other than those mentioned earlier did not significantly change between scenario runs. This is an important result for two reasons. First, the results indicate that the TECNET system performed adequately for the limited purpose of this study. That is, the TECNET output confirms the expected impacts in material and fuel consumption. Second, future impact analysis can focus on the direct impacts and their secondary consequences with more assurance that interrelated cross impacts are not causing significant effects in an apparently unrelated sector.

2.3 BASELINE SCENARIO DESCRIPTIONS

The characteristics of each scenario were developed through discussions with the Transportation Energy Systems Section of the Energy and Environmental Systems Division of ANL, personnel from JPL, and the TEC division of DOE. The scenarios were modified to conform with the input constraints of the TECNET-INFORUM system. Therefore, the first section of this chapter will review the input requirements of TECNET and will be followed by discussion of each baseline scenario and its alternatives.

2.3.1 TECSET-INFORUM Inputs

Input variables in TECSET or INFORUM may be specified either externally by the user or internally by a default file (built on IRT data). If the default file is not used, the variable can be specified (with some exceptions) for any given year. The basis of IRT data on future engine technology was the JPL Publication, Should We Have a New Engine. Due to budget and time constraints, only GNP and percent engine penetration for each size class of car are used as inputs (Reference 1). One GNP figure is developed for each scenario.

2.3.2 The Moderate Economic Growth Scenario

The Moderate Economic Growth scenario portrays a growth and consumption-oriented U.S. society constrained from reaching "success" by rates of technological innovation and resources much like those of recent history. The

TECNET derived Moderate Economic Growth scenario is based on long-term historical rates of growth of GNP and on assumptions of eventual full substitution of the alternative engines for Otto engines in various size class sectors of the auto industry. The reasoning and computations behind the selected GNP and substitution rates will be explained in the following sections.

2.3.2.1 GNP Estimation

GNP is estimated by using the predicted size of the employed labor force and multiplying by productivity. The following formula was used to estimate GNP in any given year.

GNP = (1 - UNR) * CLF * PRD

where:

GNP = total Gross National Product in 1967 dollars,

CLF = civilian labor force, consisting of those working and unemployed persons seeking work (Reference 6).

UNR = unemployment rate, representing the number employed as a percent of the civilian labor force (Reference 6).

PRD = productivity, $1000 Gross National Produce per employee.

Each independent variable was estimated for selected years after comparison with previous studies conducted by Doggett, Meyers, and Patterson (Reference 15), the Bureau of Labor Statistics (Reference 16), Jack Faucett Associates (Reference 14), and the Bureau of Economic Analysis (OBERS) (Reference 17). Table 2.17 shows the civilian labor force growth estimates compiled from the above sources (except for OBERS, which does not estimate this variable). General agreement among these studies was found within 1.0% for 1980-1990 for these variables. Recent trends indicate a lower than commonly projected growth rate through 1980. As a result, we assume a 1.00 annual percent increase in the civilian labor force through 1990 and then adopt the Faucett .8% growth rate to 2000. Thus, our selected growth rates for the moderate growth scenario are slightly lower than, but very similar to, most values used in the other studies surveyed.

Table 2.18 summarizes the productivity per worker projections of the previously cited studies, as well as those predicted by the OBERS study (Reference 12). A range of growth in productivity from 1.4% to 3.8% is exhibited in the initial period, but by 1985, this range narrows considerably to 2.0% to 2.9%. This convergence arises in part because there is no consensus on whether productivity growth rates will increase or decline through 2000. Faucett assumes a decline from 3.8% in 1975-1980 to 2.8% in 1995-2000; TECNET assumes an increase from 1.4% to 2.0%; and OBERS projections are constant at 2.9%. In this study, we use a constant 2.3% rate of growth in productivity. Our selected rate is slightly lower than most values used in the other studies surveyed, but is higher than previous TECNET projections.

Table 2.19 summarizes the unemployment rate projections of previous works. This study uses 7.0% from 1977-1980, 5.5% from 1980-1985, 5% from 1985-1990, and 4.5% from 1990-2000. These estimates are inconsistent with previous assumptions on the civilian labor force and productivity growth rates in the sense that they are slightly more optimistic than previous TECNET assumptions but somewhat less optimistic than the unemployment projections of other studies.

Table 2.20 summarizes the inputs to the GNP model, and Table 2.21 shows the resultant GNP projections. The compound percent rate of growth was calculated for various intervals which were then compared with previous work. Table 2.22 shows the comparison of GNP growth rates used in this study to those of previous studies. These projections are extremely close to BLS 1976 (Reference 11) results through 1985, and OBERS 1976 (Reference 17) projections from 1985-2000. Only in the 1985-1990 period are estimated growth rate projections used for this study higher than those of the prior studies. Rather than allow the growth rate used to be highest of the set of available projections, the growth rate for 1985-1990 was adjusted downward to 3.3%. This is midway between the OBERS and Faucett moderate growth projections (Reference 14). It also reflects a more uniform decline in the growth rate from 1980 to 1995 than initially projected. For the short-term, the Bureau of Labor Statistics' GNP growth rate estimates probably represent the best estimates of available projections. Since the ANL projections were so close to the BLS (1976) 1977-1985 estimates, the BLS rates are used in this study for that period.

Table 2.17 Growth Rates in Civilian Labor Force Used in Selected Studies

Study	Rate for Interval from: 1972 to 1980	1980 to 1985	1985 to 1990	1990 to 2000	2000 to 2025
TECNET (Doggett et al., ref. 15)	.9	0.9	1.0	1.0	0.5
BLS 1976 (ref. 11)	1.87	1.32	.94	--	--
BLS 1973 (ref. 18)	1.7	1.01	--	--	--
FAUCETT (ref. 14)	2.0	1.2	1.0	1.0 to 0.8	--

Table 2.18 Productivity Growth Rates for the Civilian Labor Force Used in Selected Studies

Study	Rate for Interval from: 1960 to 1976	1975 to 1980	1980 to 1985	1985 to 1995	1995 to 2000
TECNET (Doggett et al., ref. 15)	--	1.4	1.4	2.0	2.0
BLS 1976 (ref. 11)					
Fast Economic Recovery	--	2.4	2.7	--	--
Slow Economic Recovery	--	2.3	2.7	--	--
FAUCETT (ref. 14)	--	3.8	2.7	2.8	2.8
OBERS (ref. 17)					
1972	--	2.9	2.9	2.9	2.9
1977	--	2.7	2.7	2.6	2.6
Actual (ref. 19)	2.4	--	--	--	--

Table 2.19 Unemployment Rates in the Civilian Labor Force Projected in Selected Studies

Study	1975	1976	1977	1980	1985	1990	1995	2000
	Year							
TECNET (Doggett, et al., ref. 15)	--	--	7.5	--	5.0	--	--	5.1
BLS 1973 (ref. 15)	--	--	--	3.9	4.0	--	--	--
FAUCETT (ref. 14)	--	--	--	5.5	4.5	4.5	4.5	4.5
OBERS (ref. 17)								
1972	--	--	--	4.0	4.0	4.0	--	4.0
1976	--	--	--	5.0	4.5	4.0	--	4.0
Actual (ref. 19)	8.5	7.7	7.0	--	--	--	--	--

Table 2.20 Summary of Input Projections

Input	Absolute Value 1977	Rate for Interval from: 1977 to 1980	1980 to 1985	1985 to 1990	1990 to 2000
Civilian Labor Force	98.6	1.0%	1.0%	1.0%	.8%
GNP per worker ($77)	20.7	2.3%	2.3%	2.3%	2.3%
Unemployment Rate	7.0	5.5%	5.0%	4.5%	4.5%

Table 2.21. GNP Projections Based on Input Assumptions in Table 2.20.

Year, Growth Rates, Results	Civilian Labor Force	GNP per Worker[a]	Unadjusted GNP[b]	Minus	CLF	Unemployment Rate	GNP/Worker[a]	Potential GNP Lost through Unemployment	ANL Projected GNP	Inputted GNP	Percent Annual Growth Rate
1977	98.6	20.7			98.6	.07	20.7				
			2,041.02					142.87	1,898.1	1,890.1	-
1980	101.2	22.16			101.2	.055	22.16				
			2,242.73					123.34	2,119.38	2,113.98	3.75
1985	107.6	24.83			107.6	.05	24.83				
			2,672.0					133.59	2,538.4	2,518.06	3.67
1990	113.1	27.82			113.1	.045	27.82				
			3,146.4					141.59	3,004.81	2,961.98	3.43
2000	122.4	37.92			122.4	.045	37.92				
			4,271.10					208.86	4,062.24	3,980.62	3.06

[a]The productivity numbers are based on 1977 dollars.

[b]The term unadjusted indicates total possible GNP.

Table 2.22. Comparison of ANL GNP Growth Rate Projections with Other Studies

	Rate for Interval from:				
Study	1977 to 1980	1980 to 1985	1985 to 1990	1990 to 1995	1995 to 2000
TECNET	3.20	3.20	2.70	2.70	2.70
BLS					
1976	3.78	3.57	--	--	--
1973	4.16	2.15	--	--	--
FAUCETT (moderate)	5.80	3.70	3.20	3.20	3.00
OBERS 1976	3.40	3.40	3.40	3.00	3.00
ANL					
initial	3.75	3.67	3.43	3.06	3.06
final	3.78	3.57	3.30	3.00	3.00

For the longer term, from 1990 to 2000, the OBERS (1976) rates were employed for similar reasons. Table 2.23 shows the GNP inputs in 1977 dollars used for the resulting moderate economic growth scenario. Table 2.24 shows the GNP inputs used in 1971 dollars.

2.3.2.2 Advanced Engine Penetration Rates

The penetration rates for the Brayton and Stirling engine were determined in consort with the Technical Staff of the Jet Propulsion Laboratory. The moderate economic growth assumption implied total car sales of 13,500,000 per year for 1990 to 2000. This figure is midway between the Faucett 1990 projections of approximately 13 million in 1990 and 14 million in 2000. JPL has also assumed 14 million new car sales in 2000. Car size class projections are not obtainable from the auto industry because of proprietary restrictions. To retain some degree of compatibility with previous DOE-sponsored TECNET work, the TECNET classification percentages (17% small, 18% medium, and 65% large) were used through 1985. From 1985-2000, the percentages were changed to 25% small, 25% medium, and 50% large to reflect likely growth in small cars caused by fuel costs or congressional/regulatory action.

For the baseline scenario, 100% Otto cycle engines was assumed from 1977-2000 for all size class cars. This allows comparison of alternative engine futures to these where there are no drastic technological changes from the present. This baseline scenario was named ARGON I. Table 2.25 summarizes the ARGON I inputs to TECNET. The ARGON II alternative assumed a substitution of the Brayton free-turbine engine for the Otto cycle engine. The Brayton free turbine was assumed to penetrate the medium size, large size, and pickup-van classifications. This occurs as a result of efficiency versus volume of space occupied by the Brayton such that larger engines are more efficient. The TECNET model in present form does not allow alternative engine substitution in the pickup-van market.

The average time in constructing new engine production line is about three years. Auto companies historically have amortized these lines over 10 to 20 years. Thus, if an alternative engine is producible in 1987, it would be 1990 before mass production could begin. If a conventional engine line is

Table 2.23 Target Gross National Product, Moderate Growth Scenario. (Millions of 1977 Dollars)

Year	GNP	Growth Rates
1977	1,890.4	
1978	1,961.86	
1979	2,036.02	3.78
1980	2,112.98	
1981	2,188.41	
1982	2,266.54	
1983	2,347.46	3.57
1984	2,431.26	
1985	2,518.06	
1986	2,601.16	
1987	2,686.99	
1988	2,775.66	3.3
1989	2,867.26	
1990	2,961.88	
1991	3,050.74	
1992	3,142.26	
1993	3,236.53	
1994	3,333.62	
1995	3,433.63	3.00
1996	3,536.64	
1997	3,642.74	
1998	3,752.02	
1999	3,864.58	
2000	3,980.52	
Average Growth Rate, 1977-2000		3.29

Table 2.24 **Target Gross National Product, Moderate Growth Scenario.** (Millions of 1971 Dollars)

Year	GNP	Growth Rates (%)
1980	1,435.5	
1981	1,486.7	
1982	1,539.8	3.57 per year
1983	1,594.8	
1984	1,651.7	
1985	1,710.7	
1986	1,767.2	
1987	1,825.5	
1988	1,885.7	3.30 per year
1989	1,948.0	
1990	2,012.2	
1991	2,072.6	
1992	2,134.7	
1993	2,198.8	
1994	2,264.7	
1995	2,332.7	3.00 per year
1996	2,402.7	
1997	2,474.8	
1998	2,549.0	
1999	2,625.5	
2000	2,704.3	
Average Growth Rate, 1977-2000		3.29 per year

built in 1980, the earliest normal retirement date of the line would be 1990. Due to these building and amortization constraints, the most optimistic alternative engine full substitution in medium size cars was assumed to be four years. This was doubled to eight years for 100% substitution in large cars since there was assumed to be twice as many required production lines (50% of the market as opposed to 25%). The earliest possible production for Braytons was asumed to be 1990. Therefore, starting in 1990, a 25% per year substitution into the medium car market was initiated, resulting in full substitution of the market by 1994. For the large car market with the same number of lines per year being converted, the penetration rate is 12.5% per year, leading to complete substitution of the full sized car market by 1998. The TECNET system required these percentages be converted into percent of the total new car sales. Table 2.26 summarizes this adjusted substitution inputs into TECNET.

The ARGON III alternative assumed a full substitution of the Stirling engine into all size cars starting in 1992. The same logic cited earlier was used to establish an assumption of 100% substitution in the small and medium size market in four years, and full substitution into the large car market in eight years. Table 2.27 summarizes the inputs to TECNET.

Table 2.25 Market Penetrations (Market Shares for New Automobiles by Size, Class and Energy Type, %)
Scenario I - ARGON I

	ICE		
Year	Small	Medium	Large
1975	17.00	18.00	65.00
1985	25.00	25.00	50.00
1989	25.00	25.00	50.00
1993	25.00	25.00	50.00
1997	25.00	25.00	50.00
2000	25.00	25.00	50.00

Note: Values for intermediate years are interpolated linearly.

Table 2.26 Market Penetrations (Market Shares for New Automobiles by Size, Class and Energy Type, %)
Scenario II - ARGON II

	ICE			Brayton	
Year	Small	Medium	Large	Medium	Large
1975	17.00	18.00	65.00	0.00	0.00
1985	25.00	25.00	50.00	0.00	0.00
1989	25.00	25.00	50.00	0.00	0.00
1993	25.00	0.00	25.00	25.00	25.00
1997	25.00	0.00	0.00	25.00	50.00
2000	25.00	0.00	0.00	25.00	50.00

Note: Values for intermediate years are interpolated linearly.

Table 2.27 Market Penetrations (Market Shares for New Automobiles by Size, Class and Energy Type, %)
Scenario III - ARGON III

	ICE			Stirling		
Year	Small	Medium	Large	Small	Medium	Large
1975	17.00	18.00	65.00	0.00	0.00	0.00
1985	25.00	25.00	50.00	0.00	0.00	0.00
1991	25.00	25.00	50.00	0.00	0.00	0.00
1995	0.00	0.00	25.00	25.00	25.00	25.00
1999	0.00	0.00	0.00	25.00	25.00	50.00
2000	0.00	0.00	0.00	25.00	25.00	50.00

Note: Values for intermediate years are interpolated linearly

2.4 THE TECNET METHODOLOGY

Because of its previous use in simulating Brayton and Stirling engine production impact assessment, Argonne National Laboratory (ANL) and the Jet Propulsion Laboratory (JPL) decided to also use the DOE/TEC impact analysis system, TECNET, as the major analytical tool for ranking the primary and secondary macroeconomic changes accompanying different levels of alternate engine substitution. One unique element of this work is its comparison of alternate scenarios with Brayton and/or Stirling engines to baseline scenarios with current technology.

2.4.1 Theoretical Description of TECNET

The TECNET model is designed to examine, in a long-range forecasting framework, the total energy consequences of alternative transportation strategies. TECNET is comprised of six separate modules, each of which performs a specialized function in projecting alternative policy or technology implications for future transportation energy demands. The model is specifically designed as an energy impact model but will be used in this study as an economic impact model. Figure 2.2 outlines the TECNET system. Because this study is only peripherally concerned with energy and pollution, only the TECSET (TRANS) and INFORUM modules are important. The TECSET module portrays the transportation sector materials use, fuel use, and travel patterns. The INFORUM module can trace these direct impacts through the economy employing its input/output structure. These two modules are discussed in detail below.

The TECSET module is incorporated in the TRANS Module. TECSET is a preprocessor system that is used in the selection of scenario sensitive input parameters. TECSET includes information on the energy and materials requirements of alternative automobile technologies (e.g., Brayton, Stirling). Estimates of the materials and energy consequences of alternative scenarios are then used by the TRANS and INFORUM modules of TECNET. It is important to note that a partial or full Brayton or Stirling engine penetration scenario can be put into the TECSET module.

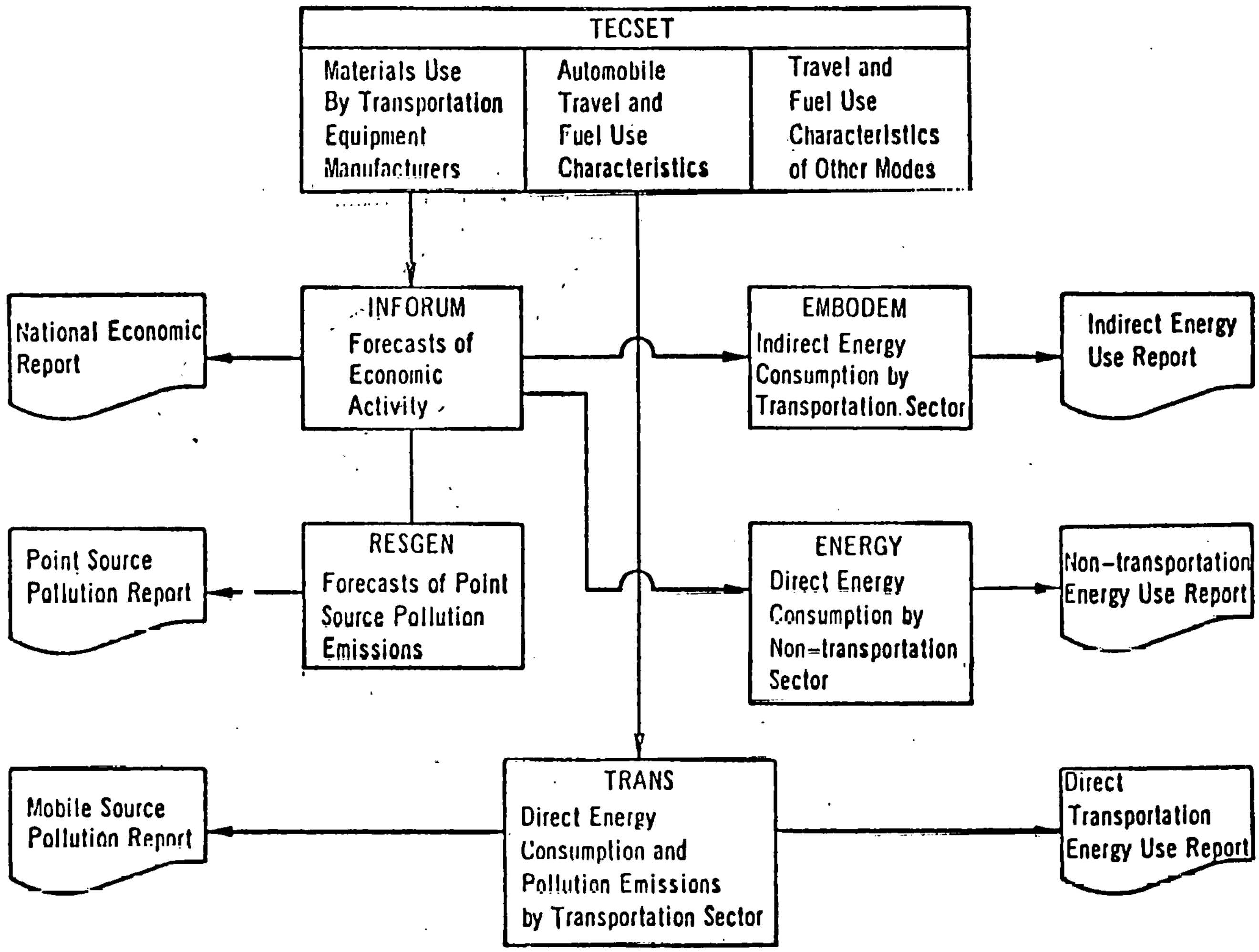

Figure 2.2. Theoretical Structure of TECNET

The core of the TECNET system is the Interindustry Forecasting Model of the University of Maryland (INFORUM). INFORUM is a highly developed economic forecasting system that combines a long-range econometric growth module to project final demand, a module to generate annual nonconsumer capital investment on the basis of the past output levels of the consumer and government elements of final demand, and an inter-industry input-output (I-O) module to generate annual output and employment of each of 185 economic sectors. Figure 2.3 shows the INFORUM module. INFORUM values are stated in dollars.

2.4.2 TECNET Advantages and Disadvantages

Within the time and money constraints set for this project, the TECNET system appears to provide the best analytical tool currently available. There are several reasons for this conclusion. First, TECNET has an existing preprocessor that has been tested by the Transportation Energy Conservation (TEC) Division of the Department of Energy (DOE). Second, the model has as its core a proven 185 sector I-O model (INFORUM). Third, the existence of this model permitted us to concentrate on scenario building and socioeconomic impact analysis without undue expenditures of man-hours building a preprocessor.

An input-output model is a type of general equilibrium model which divides the economy into sectors (185 in the case of TECNET) and uses as inputs technical coefficients (which vary overtime in the case of TECNET) relating the output of one sector to the input of another sector and final demand. As a result, an input-output model does not fully account for the effects of changes in relative prices because the production process is defined in terms of the technical coefficients. Hence, its results may be relatively insensitive to changes in price. With the impacts predicted by this study, there could be price adjustments in several sectors resulting in changes in demand which are not taken into account by the TECNET model. Also, the input-output model embodied in the TECNET model considers only national sectors whereas many of the impacts are quite regional in nature. Thus, the regional impact could be much greater than that predicted by the model. For example, aluminum production is located in only two regions of the U.S. and is

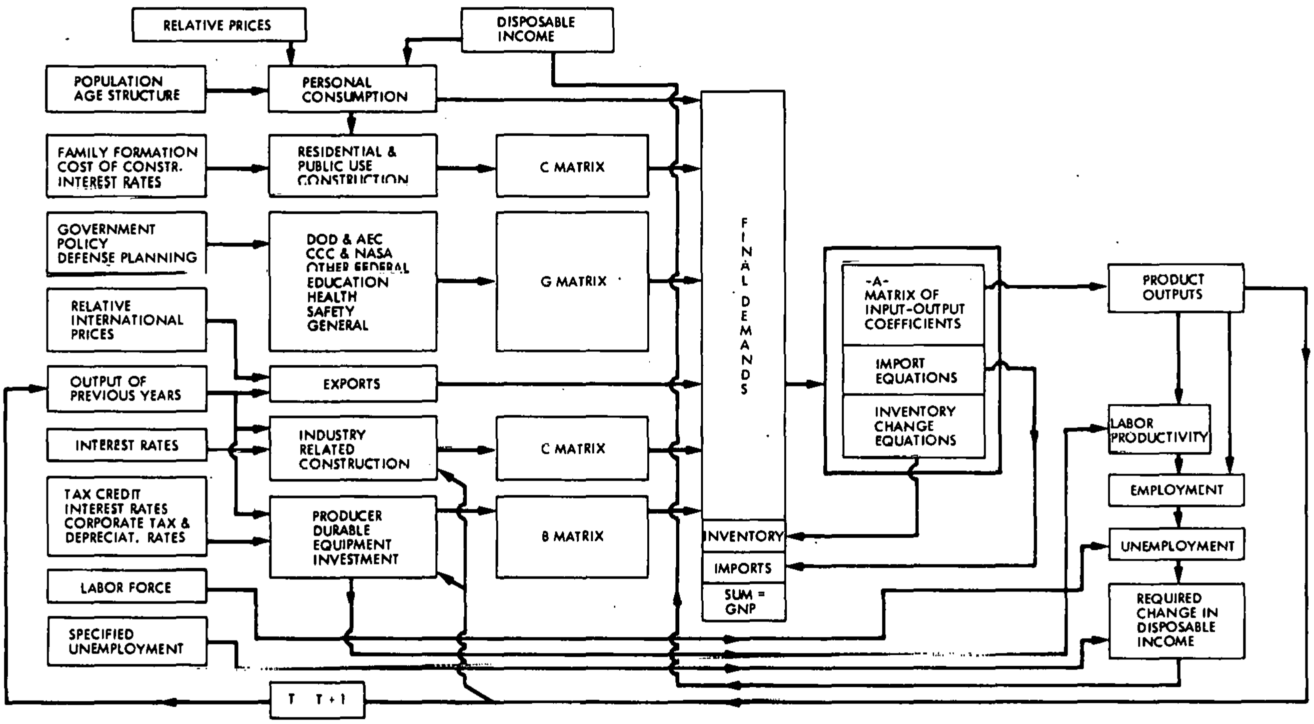

Figure 2.3. Theoretical Structure of INFORUM

quite electricity sensitive. Although impacts in electricity demand from increased aluminum production have relatively little national impact, they could result in significant local impacts.

The TECNET system is not without serious disadvantages. First, the INFORUM model does not sufficiently disaggregate the nonferrous alloy mining sector to allow adequate sensitivity analysis of mature Brayton engine penetration. Four superalloy ores that will be significantly impacted by the mature Brayton (tungsten, cobalt, magnesium, chromium) are accounted for under one sector (nonferrous ores). Second, changes in fuels required by alternative engines are handled questionably in the model. The underlying assumption is that changes in energy requirements will be distributed within the same refining, storage, and distribution infrastructure that provides present energy for automobiles. Third, the preprocessor (TECSET) is an accounting-oriented model. It is not an econometrically-driven model. An econometrically-oriented model is based on functional relationships generated with historical data using regression analysis or its equivalent. An accounting system is a static modeling approach based on simple arithmetic and algebraic relationships. The basic advantage to an econometrical 16-driven preprocessor would be the inclusion of the behavior patterns of the dependent variables (vehicle miles traveled (VMT), passenger miles traveled (PMT), car size,...). Fourth, the TECSET size classifications are weight-specific rather than consumer demand oriented classifications. This classification ignores the possibility of weight reduction in full-size cars that could allow retention of a high proportion of full-size cars in the fleet mix, thus favoring Brayton penetration. Fifth, TECSET does not allow for penetration of alternative engines into the van/pickup truck classifications. Heavy Brayton engine penetration of this class appears more likely than for cars in general. Sixth, there is an inherent weakness, due to the technical coefficients base, of the I-0 model that limits it to relatively short-run (10-year) analysis. As a result, this study will forecast through 2000 rather than the year 2025 projected in TECNET. Seventh, the present TECNET-INFORUM base is not updated to include recent modifications in the INFORUM Model. International Research and Technology Corporation (IRT) and the Department of Energy are correcting the system for some of these disadvantages, but the corrections were not completed at the time of this study.

2.4.3 Comments on TECNET

The TECNET model has many disadvantages for this particular socioeconomic impact analysis. When the modifications in the model are complete, the results of this study can be modifed. It should be noted that TECNET was chosen as the basic analytical tool because it was better than the alternatives (i.e., building a new preprocessor). Many of the criticisms made here result from the detailed study of the TECNET model and its validity for this particular study. The criticisms are primarily ones of detail, but not of the conceptual structure of the model itself.

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SECTION 3.

ECONOMETRIC ANALYSIS OF AUTOMOTIVE ATTRIBUTES FOR ALTERNATIVE ENGINE

3.1 INTRODUCTION

Until recently, the attributes and number of automobiles sold and in use were determined primarily by market forces. These market conditions included the costs of producing desirable attributes such as quality, efficiency, and performance; the level and distribution of income; the demand for transportation; and the characteristics of the existing stock of automobiles. The federal government, however, has initiated a program of both research and regulation of the automobile. This program involves the pollution characteristics of new automobiles, safety standards, and target levels of automobile efficiency.

The federal regulations, especially the automobile effiency targets, have contributed to changing the typical automobile offered by domestic producers. The degree to which consumers will accept these new automobiles will be determined in the marketplace. This section examines the price and implied costs of producing automobile efficiency in combination with other desirable attributes such as quality and performance. The focus of this section is upon the market value of the fuel efficiency research goals of Brayton and Stirling engines.

In addition to price, the three key vehicle sales attributes are quality, efficiency, and performance. While these attributes are difficult to quantify, surrogate variables which are quantifiable can be developed. Quality - in this study as in other recent works - is measured by the weight of the automobile. The assertion here is that, all other things equal, the heavier the car, the higher its quality.[1] Efficiency of fuel consumption

[1]We recognize that recent efforts to downsize new offerings complicate the relationship between weight and quality. In the work that follows, we must assume that there remains a reasonably strong positive correlation between weight and perceived quality.

is measured here by the EPA/DOE per gallon rating for automobiles equipped with an automatic transmission and operated in city conditions. This rating is a direct indicator of a car's fuel efficiency and, because of fuel costs' relative share in operating costs, a good indicator of overall operating efficiency.[2] Performance is measured here, as in other studies, by an automobile's horsepower per pound (bhp/weight). This measure of performance places heavy emphasis on acceleration,[3] as bhp/weight is basically a measure of an automobile's acceleration potential.

3.2 BACKGROUND

The purpose of this analysis is to determine if consumer response to fuel efficiency is sufficient for alternative engines such as the Brayton or Stirling to be viable competitors to the conventional Otto cycle engine. To do this, it is necessary to make certain assumptions about the behavior of the industry and/or the firms within the industry. The first assumption is that the firms desire to maximize total corporate profit, and therefore require that an alternative engine, if substituted for a conventional engine in some part of its sales mix, would result in an overall corporate profit no less than that which would be achieved by using totally conventional engines. The second major assumption is that the manufacturers in response to changes in market demand, federal standards, or production costs have some degree of discretion in setting not only prices and quantities, but also values of other choice variables such as size, acceleration, quality, fuel economy, design lifetime, etc.

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[2]According to a recent study by Hertz, fuel and lubrication account for approximately 72% of three-year variable costs (Hertz News, 10/31/77).

[3]While JPL has an Otto Equivalent Engine (OEE) concept that is not defined on equal horsepower per pound, a recent JPL report (Automobile Technology Status and Projections, ATSP/JPL Assessement Report, JPL Pub. 78-71, Vol. II, 1978) uses equal bhp/weight as a measure of equivalent vehicle performance when all aspects of acceleration, including transient response, must be considered.

In simple terms, we can represent that profit which the manufacturer wishes to maximize, as follows:

Profit = Quantity x (Unit Price - Unit Cost)

The demand curve is the relationship between the price of the item and the number of items that can be sold. If we assume that this curve is downward sloping as represented in Figure 3.1, implying that one can sell a few items at a very high price or many items at a very low price, there will exist a most profitable price (and therefore quantity) for the manufacturer. Likewise, there also exists a market mechanism (albeit, significantly more complicated) for determining the most profitable values of the choice variables. Because the advanced alternative engines present a means of achieving fuel economies not easily achievable with conventional engines, the market equilibrium mechanism for selecting the fuel economies of vehicles in the market place is of central importance.

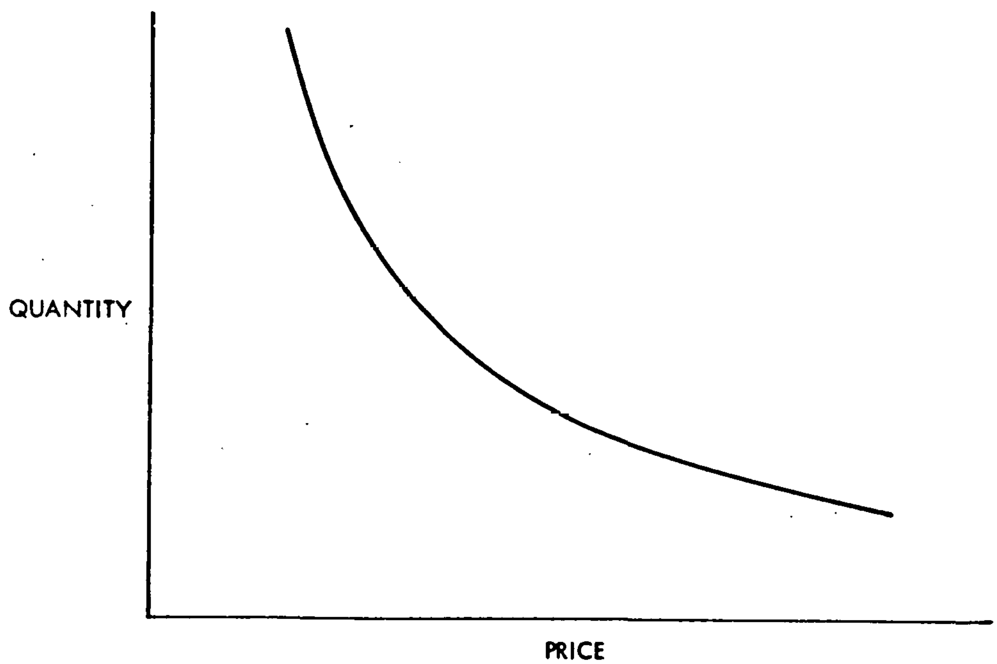

Figure 3.1. Example of Demand Curve

In simple terms, the magnitude of any choice variable such as fuel economy will be determined by the tradeoff between the consumer's desire for that attribute as represented by the price he is willing to pay and the difficulty that a manufacturer has in supplying such an attribute as represented by the cost to produce it. This is described as follows: the equilibrium relationship between the level of a choice variable and the price that a consumer is willing to pay for it is called a hedonic price curve. A hypothetical relationship for this is presented in Figure 3.2 for the case of vehicle acceleration versus the price consumers are willing the pay for acceleration.

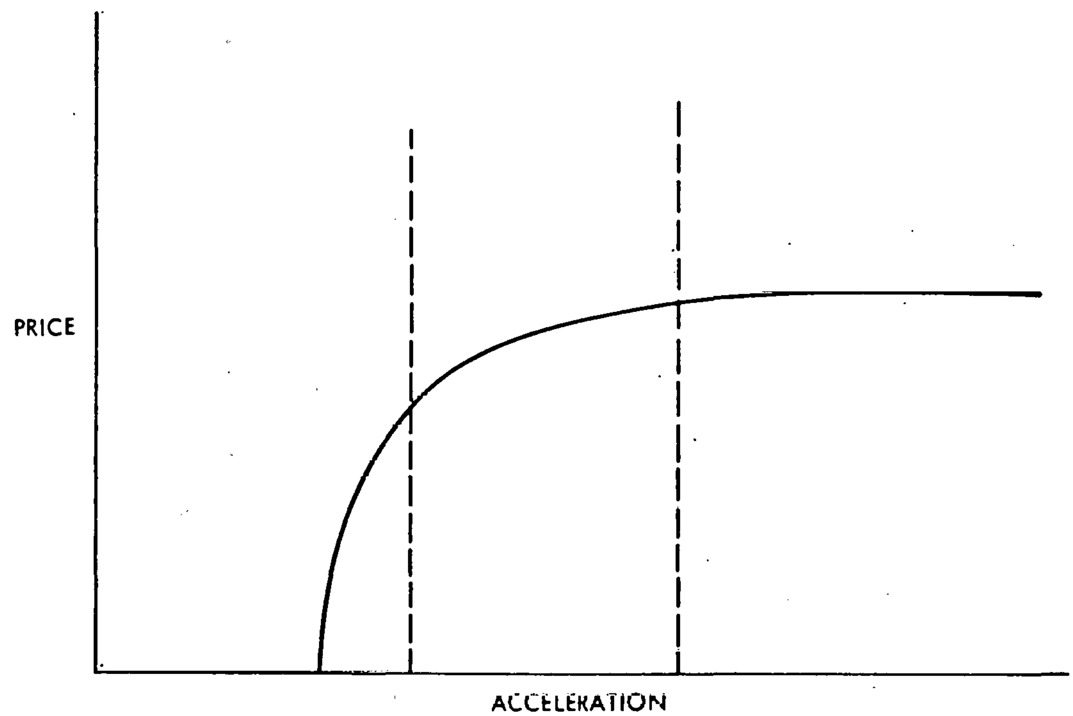

Figure 3.2. Example of Hedonic Price Curve

Near the minimum acceptable level, the price curve rises very steeply representing high value placed upon one more unit of acceleration for such low performance vehicles. Beyond this, in the region where we find most vehicles, there is a smaller value associated with higher levels of performance. Finally, no more value is placed upon increased performance presumably because such performance is not realizable on normal streets and roads. Similar curves could be developed for other choice variables such as fuel economy, quality, durability, etc.

In attempting to meet the consumers desires for an increased level of these choice variables, a manufacturer is usually faced with an increasing cost curve. Increasing the acceleration of a vehicle will entail installing a higher horsepower, high performance engine which will entail higher cost. Such a relationship is represented in Figure 3.3.

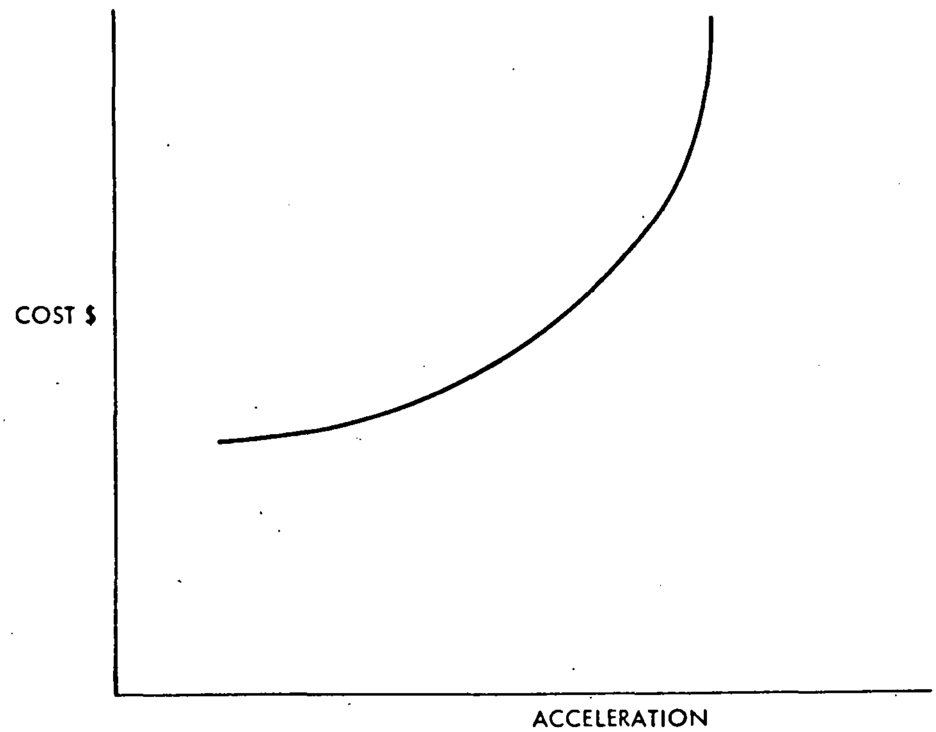

Figure 3.3. Example of Cost Curve

Such a cost curve is also applicable to the situation in which a manufacturer cannot make a change in the value within some technology but rather must make discrete changes in technologies. In this case, the cost curve is represented by the envelope covering the discrete choices as presented in Figure 3.4, but the fundamental concept remains unchanged.

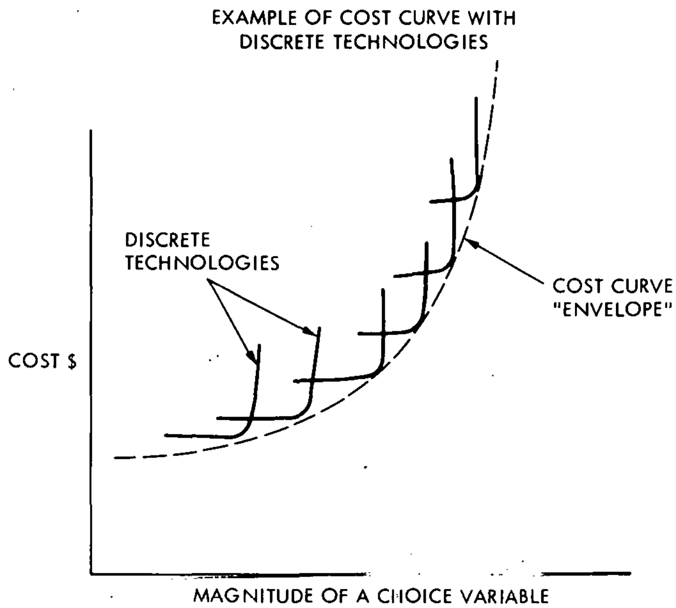

Figure 3.4. Example of Cost Curve with Discrete Technologies

The actual values of the choice variables appropriate to the various automobiles which we find in the marketplace will be those which are most profitable for a manufacturer to provide. An example of this, once again for the hypothetical case of acceleration, is presented in Figure 3.5.

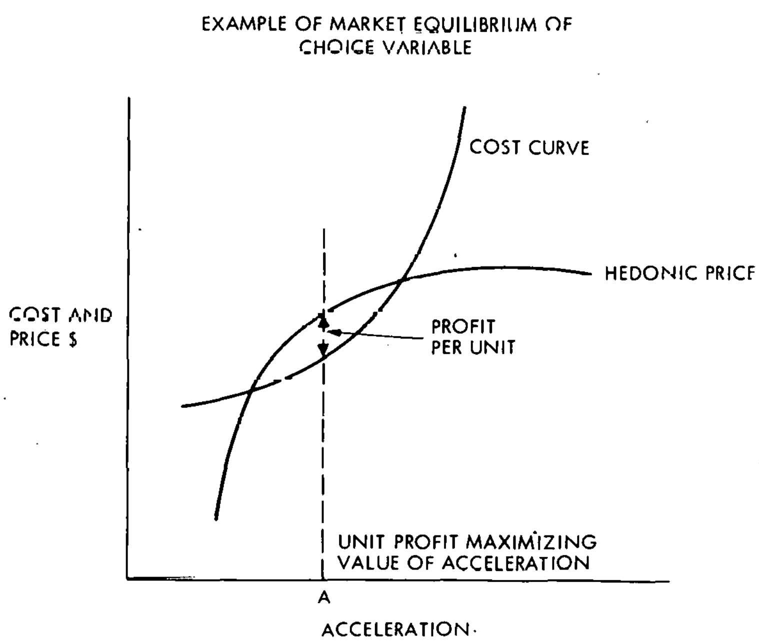

Figure 3.5. Example of Market Equilibrium of Choice Variable

Within that region where the price the consumers are willing to pay exceeds that of the cost to manufacturer, there is one value which maximizes that difference. If technological change improves a cost curve, if external forces such as an oil embargo cause a change in buyers valuation of an attribute, or if there exists an exogenous constraint such as mandatory fuel economy, the market equilibrium value of the choice variables will be shifted.

A newly developed technology with a considerably higher potential fuel economy value will not necessarily demonstrate such a level of fuel economy when it is introduced into the marketplace. The fact that it can be produced profitably does not imply that it will, in fact, be substituted over existing technologies. An example of such a situation is presented in Figure 3.6. The curves labeled cost and price are the cost curve and hedonic price functions for fuel economy. The equilibrium marketplace value is labeled E. A new technology which has a much higher potential fuel economy is shown by the dotted curve. The equilibrium level for this technology is shown with the symbol E*, and as is also the case for the "old" technology, is considerably below that of its maximum potential fuel economy. Furthermore, the equilibrium profit for the new technology is less than that of the current technology which implies that a manufacturer will not choose this even though it does possess higher fuel economy and is profitable (unless other attributes increase sales or total corporate profit.

New technologies are often recognized not to be commercially viable under present circumstances. However, if they are evaluated within a petroleum

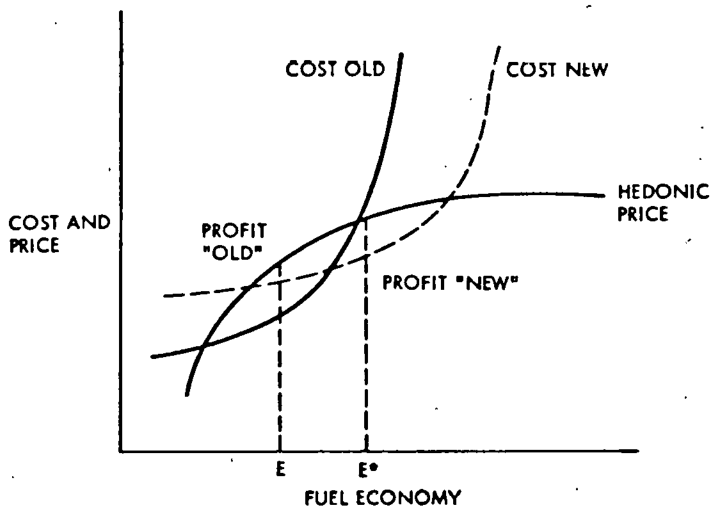

Figure 3.6. Example of Market Equilibrium for New Technology

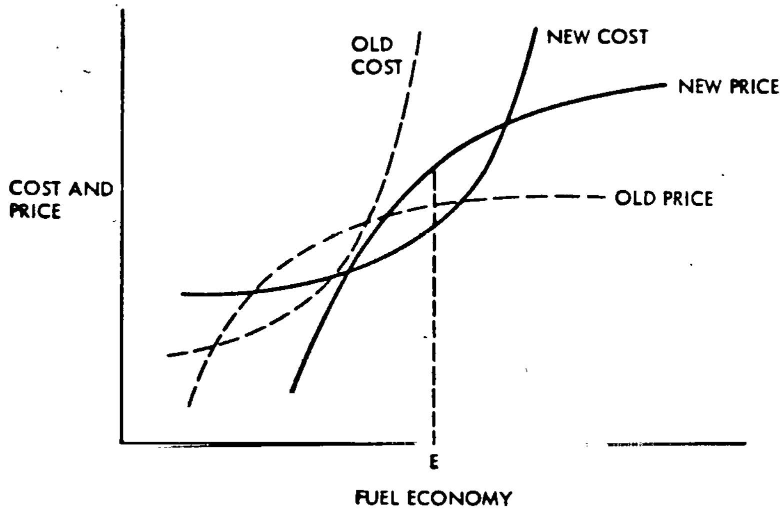

Figure 3.7. Example of Shift in Hedonic Price Curve with a New Cost Curve

constrained future, they may represent an optimal market choice. Such a case is presented in Figure 3.7. Constraints upon the availability of petroleum in the future have caused the hedonic price curve to shift upward and to the right. The result of this is that the equilibrium levels for fuel economy have improved in both the current and new technology, but now, the profitability of a new technology exceeds that of the old*. One would expect that the newly developed technology would progressively supplant the previous technology.

The key points in this discussion are as follows:

1. For the analysis of economic viability, a new technology can be characterized by cost curves for each of the choice variables.

*As the figure is drawn, the old technology equilibrium for fuel economy would be a loss minimizer, not a profit maximizer.

2. The market equilibrium levels of the choice variables for two different technologies would be expected to be different, due to the different shapes of the respective cost curves. In other words, it is unlikely that the marketplace would choose all values of all choice variables to be identical for the two technologies with the sole exception of fuel economy.

3. New market conditions, represented by a change in the hedonic price curve for fuel economy, sufficient for a new technology to become viable in the marketplace could improve the fuel economy with the old technology.

The following section describes an attempt to quantify from historical data the hedonic price curves for the attributes mentioned and to form some inferences on the viability of new engine technologies.

3.3 STRUCTURE OF THE CONCEPTUAL MODEL

The qualitative relationship described above can be cast into a simple mathematical model for examining the economic viability of new engine technologies. We can assume that a manufacturer simply desires to maximize net profits resulting from the sales of several different models of cars. Since his choice variables are price, fuel economy, and acceleration (in this simplified case), we can write these relationships as follows.

3.3.1. Profit

$$\text{Profit} = \sum_{\substack{\text{Sales} \\ \text{Classes}}} Q_i * (P_i - C_i)$$

Where: Q_i = Demand (Sales) of Class i

P_i = Unit Price of Vehicle in Class i

C_i = Unit Cost to Product Vehicle in Class i

The unit cost for a sales class is a function of both quantity produced and the values of all of the choice variables. Because price and quantity are related, the hedonic price relations can be cast into quantity relations and incorporated into the demand curve. In other words, cost is a function of quantity (thereby price) and the choice variables; demand (Q) is a function of price and the choice variables.

In addition, the demand for one sales class of car will depend not only on its price (and fuel economy, acceleration, etc.) but also on the price (and fuel economy, etc.) of the other sales classes.

3.3.2. Marginal Conditions for Maximization

The maximum of the profit function with respect to price, fuel economy, etc., will occur when the partial derivatives of the profit function with respect to each of these variables are zero. Hence, the resultant set of equations can be solved to yield the values of these variables which would be expected to manifest in the marketplace.

For all i (Sales Classes)

$$\frac{\partial \text{Profit}}{\partial P_i} = 0$$

$$\frac{\partial \text{Profit}}{\partial \text{Fuel Economy}_i} = 0$$

$$\frac{\partial \text{Profit}}{\partial \text{Acceleration}_i} = 0$$

In addition, the attempt to maximize net profits is constrained by the governmental requirement for corporate average fuel economy (CAFE). This constraint can be written as follows:

$$\frac{1}{\text{CAFE}} = \sum_{\substack{\text{Sales} \\ \text{Classes}}} \frac{Q_i}{Q_{total}} \frac{1}{\text{mpg}_i}$$

We may now find the values of price and quantity, fuel efficiency, and acceleration which represent the profit maximizing choices under a fuel economy constraint for conventional (Otto engine technology).

For the evaluation of new alternate engine technologies, we may substitute the alternate engines in the form of new cost curves into one or more of the sales classes and examine if the new equilibrium values for the choice variables are improved over the conventional technologies and, more importantly, that the profit is at least as great as with the conventional engine. For a petroleum constrained future where we would expect that the viability of the advanced engines would be improved, we may postulate a new hedonic price curve for fuel economy and reevaluate the respective positions of both the conventional and the alternative engine technologies.

3.4 HEDONIC FORMULATION

The approach selected for estimating costs involved using the hedonic price (or cost) methodology. The hedonic price and/or cost approach generates estimates of attribute price and cost coefficients by regressing the price of a unit on that unit's attributes. Actual input or cost data were not available at a level of disaggregation that would have allowed us to estimate directly the actual production and distribution costs associated with varying the attribute mix of a new automobile using either conventional engines (Otto) or alternative engines such as a Brayton or Stirling. What was available, in a more or less convenient form, were the prices and characteristics of the various automobiles that make up the additions to the fleet.

The first step in the hedonic approach involves obtaining an estimate of the variation in the selling price of an automobile owing to variations in the attributes of the automobile. The novel aspect of our formulation is the specific attributes included in the hedonic index. Very few of the existing hedonic estimations of automobile prices include all of the specific attributes employed in this study. In fact, to the best of our knowledge, there is only one other hedonic estimation involving both fuel efficiency and performance. Most of the existing hedonic estimates focus on attributes other than fuel efficiency and performance.[4]

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[4]For example, see Ohta and Griliches, Automobile Prices Revisited: Extension of the Hedonic Hypothesis, and K. Train, Consumers' Response to Fuel Efficient Vehicles: A Critical Review (Cambridge Systematics, Inc.: West Berkeley, California). The other study which considers both efficiency and performance is Cassella and Rabe (1978).

The general form of the hedonic equation we estimated was:

$$P = b_0 + b_1E + b_2W + b_3A \qquad \text{eq. 1}$$

where E is a measure of fuel economy, A a measure of performance and W the weight of the automobile.

Estimating a price equation such as eq. 1 is not necessarily the same as estimating how the costs and/or consumer valuations of an automobile change in response to changes in its attributes.[5] The estimated coefficients b_1, b_2 and b_3 reflect the observed variation in the market price of an automobile associated with variations in the attributes: fuel economy, performance and weight. However, we can interpret these coefficients as estimates of the costs of varying the attribute levels if, as is likely to be the case, all major producers face roughly similar costs of production. We assume that the unit costs of producing an attribute, at least for automobiles in the same class, are constant and that there are no monopoly or supracompetitive profits in the industry.

In Figure 3.8, the line labeled C represents a hypothesized relationship between the price of an automobile and a single attribute, its fuel efficiency measured in miles per gallon (mpg). Under the conditions enumerated above, estimating the slope of this relationship (C) is sufficient for establishing the costs of varying fuel economy, at least for automobiles with mpgs between 10 and 14. Of course, if there is a significant element of monopoly, and, hence, some pure profit present in the industry, estimates of the price equation, C, will not directly yield cost information. In this case, some specific markup or profit structure must be imposed on the problem. For example, we might assume that the actual cost function is Z and that the markup does not vary with the attribute levels. Hence the marginal cost of mileage (MC_1) would simply be:

$$MC_1 = b_1 \times (1 - M) \qquad \text{eq. 2}$$

where b_1 is the estimated slope of C and M is the markup over unit cost.

5See Rosen (1974) for a more detailed treatment of this topic.

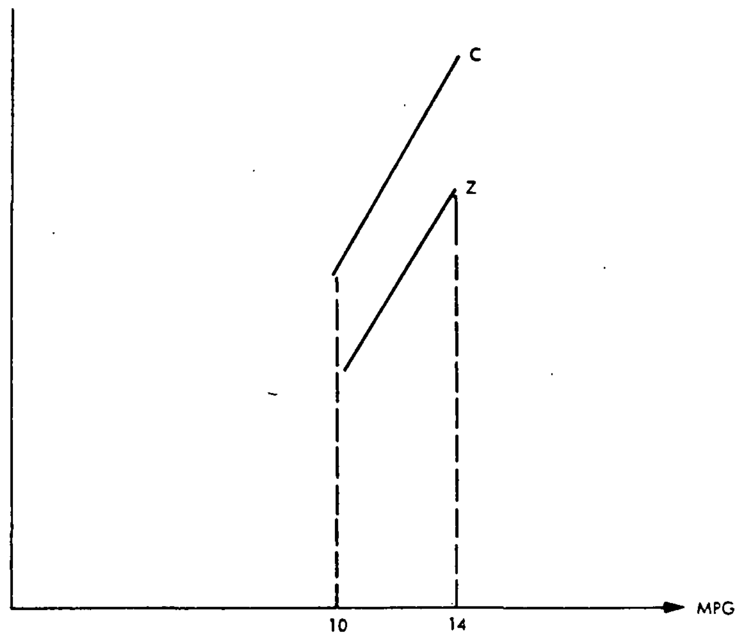

Figure 3.8. Automotive Price and Cost vs. Fuel Economy

Though a constant markup formulation greatly simplifies the process of obtaining cost information from a price equation and has been used in similar studies (Ohta 1974), it is not without problems. There are both theoretical and practical objections to such a formulation. The theory of attribute pricing under monopoly (Mussa and Rosen 1978) suggests that markups will increase as the attribute level increases. Empirical data on markups in this industry is sparse, but a study performed by LeRoy Lindgren for the National Academy of Sciences suggests a price equation of the following form:

$$\text{Retail Price} = (1.4 + .0003 \text{ Manf. Cost}) \times (\text{Manf. Cost}) \qquad \text{eq. 3}$$

and hence a variable markup over cost of the form:

$$\text{Markup} = 1.4 + .0003 \times \text{Manf. Cost.}$$

In the Lindgren formulation, how significant the increases in markups are - or, equivalently, how poorly we approximate actual behavior with a fixed markup formulation - will depend on the absolute magnitude of the cost variation under consideration. For relatively small changes in cost, induced either by small changes in relatively expensive attributes or moderate variations in inexpensive attributes, the fixed markup formulation may be an acceptable approximation.

3.4.1 Hedonic Estimation

Using data obtained for domestically-produced cars, we initially estimated an equation of the following general form:

$$P = b_0 + b_{S1}ES + b_{M1}EM + b_{L1}EL \qquad \text{eq. 4}$$

$$+ b_{S2}AS + b_{M2}AM + b_{L2}AL$$

$$+ b_{S3}WS + b_{M3}WM + b_{L3}WL$$

The subscripts refer to the size class of car involved: S refers to small cars, which in this sample are all automobiles weighing less than 3250 pounds; M refers to mid-size cars or those weighing between 3250 and 4000 pounds; and L refers to large cars or those weighing in excess of 4000 pounds. Fuel economy, E, is taken to be mpg as calculated by the Environmental Protection Agency (EPA) in urban drivng with an automatic transmission and performance is measured by brake horsepower (bhp) per pound. Automobiles will fall ito one of the weight classes and the variable corresponding to a particular weight class and attribute reflects the characteristics of the car. For example, an observation might describe a 3700 pound car and WM would equal 3700, the auto's weight, while WS and WL would be zero. Similarly, ES, EL, AS and AL would be set to zero for a 3700 pound automobile, while EM and AM would reflect the automobile's efficiency and performance attributes. Data from model years 1975 through 1978 are used in the estimation. The total number of observations was 401, of which 112 were for small cars, 154 for mid-size and 135 for large cars. Base year for the estimation is 1978; hence all prices are given in terms of their 1978 levels. Price, weight and horsepower information were obtained from relevant issues of Automotive News, while mileage data were obtained from the EPA's Gas Mileage Guides for the appropriate years.[6]

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[6]Problems with the accuracy of EPA mileage estimations, particularly for highway use, led us to employ the urban cycle data. These were for 49 state models with automatic transmissions.

The estimation of the preliminary form of the equation appears in Table 3.1. In addition to the variables appearing in Eq. 3.4, this regression includes category-specific controls for model year. These are labeled YEARTJ where T is the model year ('75 through '78) and J is the automobile category or class (S, M, and L).[7] The YEAR variable allows the level of the predicted automobile price to vary with the class and year of the automobile. These controls allow the estimated price to reflect changes such as pollution or safety regulations, as well as industry-wide changes in standard equipment such as radios. While many of the controls are not statistically significant, those for small cars are all significant and positive, although the differences among the coefficients are not statistically significant.

The hypothesis underlying the estimates in Table 3.1 is that the three major classes of automobiles have different coefficients for all attributes. That is, the variation in the price of an automobile due to variations in an attribute level depends on whether the car is small, mid-size or large. As we can see for the mileage coefficients, the point estimates for the mid-size and large cars are extremely close. In fact, even though the point estimate of the mileage coefficient for a small car is less than the coefficients for mid-size and large cars, the hypothesis that all fuel economy coefficients are, in fact, the same cannot be rejected statistically.[8] The results of imposing a single fuel economy coefficient across the size classes appear in Table 3.2. With the exception of the single coefficient on E, the regression results are entirely similar to those in Table 3.1.

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[7]Because the equation is estimated with an intercept, one of the controls had to be omitted. The omitted control in this equation is YEAR78L and its effect is absorbed into the intercept.

[8]The statistic for testing the hypothesis that the mileage coefficients are equal has a value of .57 and follows $F_{2, 380}$ distribution. The test statistic would have to be larger than 3.02 for the equality of the mileage coefficients to be rejected at the 5% level.

Table 3.1. Hedonic Price Equation
Preliminary Form[1]

Independent Variable[2]	Estimated Coefficient	Estimated t-statistic
WS	0.986	4.58
WM	1.856	9.11
WL	1.204	8.36
ES	60.94	2.29
EM	102.9	3.01
EL	94.99	2.74
AS	12464.	1.48
AM	33468.	4.12
AL	98761.	10.1
YEAR75S	4287.	2.75
YEAR75M	-396.9	0.23
YEAR75L	49.30	0.39
YEAR76S	4076.	2.59
YEAR76M	-607.6	0.36
YEAR76L	-346.5	3.05
YEAR77S	4102.	2.56
YEAR77M	-262.6	0.15
YEAR77L	-220.5	1.76
YEAR78S	4311.	2.68
YEAR78M	-46.25	0.02
Intercept	-4435.	

Number of Observations	401
Rsquare	.771
F-Statistic (20,380)	63.9
Mean Squared Error	170446

[1] This regression is based on automobiles produced domestically by American companies and sold for less than $8000. The automobiles included in this sample account for roughly 93 percent of domestic automobile production. The dependent variable is the real price of automobiles equipped with automatic transmissions.

[2] An automobile is defined to be L or large if its weight exceeds 4000 lbs, M or mid-sized if its weight is at least 3250 lbs but not more than 4000 lbs - otherwise it is S or small. There are 135 large, 154 mid-sized and 112 small automobiles in the sample.

Table 3.2. Hedonic Price Equation

Miles per Gallon Combined[1]

Independent Variable[2]	Estimated Coefficient	Estimated t-statistic
WS	1.109	6.14
WM	1.777	10.3
WL	1.172	9.41
E[3]	81.69	4.56
AS	15545.	1.97
AM	30470.	4.34
AL	98006.	10.2
YEAR75S	3124.	4.15
YEAR75M	-57.02	0.07
YEAR75L	29.67	0.25
YEAR76S	2894.	3.82
YEAR76M	-231.8	0.27
YEAR76L	-352.0	3.12
YEAR77S	2887.	3.78
YEAR77M	119.8	0.14
YEAR77L	-222.9	1.78
YEAR78S	3093.	4.04
YEAR78M	334.8	0.39
Intercept	-4085.	

Number of Observations	401
Rsquare	.770
F-Statistic (18,380)	71.1
Mean Squared Error	170063

[1] This regression is based on automobiles produced domestically by American companies and sold for less than $8000. The automobiles included in this sample account for roughly 93 percent of domestic automobile production. The dependent variable is the real price of automobiles equipped with automatic transmissions.

[2] An automobile is defined to be L or large if its weight exceeds 4000 lbs, M or mid-sized if its weight is at least 3250 lbs but not more than 4000 lbs - otherwise it is S or small. There are 135 large, 154 mid-sized and 112 small automobiles in the sample.

[3] The variable "E" gives the miles per gallon of each automobile and is the sum of ES, EM and EL.

One source of price variation not controlled for in the estimated price equations presented in Tables 3.1 and 3.2. is the manufacturer. The results of related work by Cassella and Rabe (1978) suggest that the manufacturer may, in fact, be an important variable in hedonic equations for automobile prices.[9] In order to check for a "manufacturer effect," we introduce category-specific manufacturer controls into the price equation. These controls were of the form RJ where R = AM (American Motors), FMC (Ford), CHR (Chrysler), or GM (General Motors); and J = S (small), M (mid-size), or L (large). Introducing these controls, and then retaining them as well as the model year controls (YEARJT) when they are statistically significant, enable us to further pool the observations by category. The results of this process are displayed in Table 3.3.

When satistically significant model year and manufacturer controls are retained in the price equation, we can reduce the number of both weight and performance classes from three to two.[10] Under the specifications in Table 3.3, we cannot reject the hypothesis that small and mid-size cars have the same weight and performance coefficients.[11] While the manufacturer controls were introduced basically to refine our estimate of attribute coefficients, their coefficients are of some interest. Note that the estimates in Table 3.3 imply that all non-GM small cars sell at a discount relative to comparable GM small cars. Based on our point estimates, only American Motors small cars appear to sell at a discount with respect to Chrysler, and even here the difference is not statistically significant.

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[9]It is interesting to note that Cassella and Rabe are only able to obtain meaningful hedonic coefficients for cars manufactured by General Motors.

[10]Note that the addition of maker variables made it attractive to retain more model year size class controls.

[11]The statistic for testing the equality of the coefficients on performance and quality of the small and mid-sized automobiles had a value of 1.00 and follows $F_{2, 379}$ distribution. A value of the test statistic over 3.2 would warrant rejection of the hypothesized equality of coefficients at the 5% level.

Table 3.3. Hedonic Price Equation[1]

Independent Variable[2]	Estimated Coefficient	Estimated t-statistic
WSM[3]	1.624	14.1
WL[4]	0.919	8.64
E[5]	74.76	4.53
ASM	25323.	4.88
AL	94144.	10.6
YEAR75S	270.3	2.81
YEAR75M	-664.0	4.88
YEAR76M	-831.1	6.28
YEAR76L	-389.9	5.04
YEAR77M	-468.9	3.69
YEAR77L	-258.7	2.69
YEAR78S	201.6	2.05
YEAR78M	-253.3	2.09
AMS	-580.4	4.82
FMCS	-349.8	3.93
CHRS	-485.5	3.39
CHRM	-148.6	2.01
CHRL	-263.8	3.32
Intercept	-2614.	

Number of Observations	401
Rsquare	.783
F-Statistic (18,380)	76.6
Mean Squared Error	160492

[1] This regression is based on automobiles produced domestically by American companies and sold for less than $8000. The automobiles included in this sample account for roughly 93 percent of domestic automobile production. The dependent variable is the real price of automobiles equipped with automatic transmissions.

[2] An automobile is defined to be L or large if its weight exceeds 4000 lbs, M or mid-sized if its weight is at least 3250 lbs but not more than 4000 lbs - otherwise it is S or small. There are 135 large, 154 mid-sized and 112 small automobiles in the sample.

[3] The variable "WSM" gives the weight of small and mid-sized automobiles and is the sum of WS and WM.

[4] The variable "E" gives the miles per gallon of each automobile and is the sum of ES, EM and EL.

[5] The variable "ASM" gives the bhp/weight of small and mid-sized automobiles and is the sum of AS and AM.

3.4.2 Fuel Economy

According to our estimates of the price equation, the change in the selling price of an automobile due to an increase in its fuel efficiency of one mpg is approximately $75. If the automobile market is competitive, then the cost of additional fuel efficiency will also be approximatedly $75/mpg. While the number of domestic automakers is small (four) and the largest of the four is quite large (roughly 60% of the domestic market for model year 1978), competition from imports is very active and significant monopoly power, at least for the small automobile segment of the market, is unlikely. Since the fuel efficiency coefficient appears to be similar across size class, it is reasonable to use $75 as an approximation to the cost of additional mileage.

Assuming competition in the provision of fuel economy does not necessarily conflict with Lindgren's findings, the markup or price equations given above refer to manufacturing costs, not total costs. The markup above manufacturing costs may simply reflect other costs, including the non-trivial costs of distributing automobiles. If this is the case, then applying the Lindgren markup formulation to our total cost of mileage would suggest that the direct manufacturing cost of additional mpgs is approximately $53.[12] Hence, if the target for an alternative engine is formulated in terms of actual manufacturing costs, $53 would be the appropriate figure.

How does our estimate compare with other recent work on the cost of mileage? Perhaps the most directly comparable work are the estimates derived by Cassella and Rabe (1978). Using a somewhat different sample, these authors are able to obtain stable results only for General Motors cars. Here the find was that for 1972-74 GM models the list price increases by approximately $64 for each additional mpg. In 1978 prices, this would be $89 mpg. Our results - for domestic car makers and a sample more than three times as large - are very close in magnitude to this estimate.

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[12] Derived from the equation relating cost to retail price developed by Lindgren and given above.

Charles River Associates (CRA, 1979) in a preliminary report on their study of the "Impact of Fuel Economy Standards on Competition in the Automotive Industry," present some estimates on the price of fuel economy from their hedonic demand model. They find that in their 1977 data base, prices decrease by approximately $88 per gallon per hundred miles, or about $11 per mpg for subcompacts and $38 per mpg for luxury cars in the sample. Use of their coefficient of $88 (per gallon per hundred miles) and the average mpg from our sample would result in an average implied variation in price of $34 per mpg. These estimates are substantially lower than our estimate for the fuel economy coefficient and lower than the figures expected by the authors of the CRA report. On page 16 of their preliminary report, they state: ". . . the $88 estimate is untenably low. We had expected an estimate about three times as high."

At least at the margin, the price of additional mpgs must equal consumers' evaluation of these mpgs. Hence, it is interesting to compare our estimated price of mpg with estimates of the present discounted value of fuel savings due to an additional mpg. The U.S. Department of Transportation (DOT), in fact, has used the fuel savings approach to evaluate the feasibility and desirability of fuel efficiency requirements.[13] Employing the DOT assumptions about mileage, gasoline prices, and discount rates, the imputed value of an additional mpg would be $176 at the average fuel efficiency level (15.5 mpg) in our sample.[14] This figure is clearly much larger than either our estimate of the price coefficient for mpgs or than other recent estimates of the price of fuel efficiency. The value of fuel economy implied by the DOT assumptions simply does not appear to be the market value of this fuel economy. This should serve as an indicator of the difficulty and subtlety of simulating the market reaction to changes in attributes. Establishing the market response to automobiles powered by alternative engines by "reasonable" arguments is likely to be similarly problematic.

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[13]Automotive Fuel Economy Program: Third Annual Report to the Congress (January 1979), U.S. Department of Transportation, National Highway Traffic Safety Administration.

[14]Details on the DOT assumptions are in L.L. Liston and C.A. Aiken, The Cost of Owning and Operating an Automobile, Office of Highway Planning, Highway Statistics Division, U.S. Department of Transportation.

3.4.3 Performance

The measure of performance in our price equation is, as we noted previously, brake horsepower per pound (bhp/weight = A). While we are basically interested in measuring acceleration potential for this sample, horsepower per pound was the best available indicator of performance. Actual 0-60 mph times were not available for all of the models in our sample. However, using an independent data source, we were able to estimate the following relationship between acceleration - specifically, 0-60 mph times in seconds (T) - and our measure of performance, bhp/W (A).[15]

$$T = \underset{(8.65)}{29.71} - \underset{(23.89)}{450.39A} \quad \text{[16]} \qquad \text{eq. 5}$$

As would be expected, there is a very stable empirical relationship between horsepower per pound and acceleration, at least as the latter is measured by 0-60 mph time.

By combining the information in Eq. 5 and Table 3.3 we can derive an estimate of the effect of changes in acceleration on the selling price of an automobile. For small or mid-size cars our estimates imply that a reduction in 0-60 mph time of one second will increase the price by about $56; for large cars, the implied price increase for a similar gain in acceleration would be approximately $210.[17] Again, these figures, $56 and $210, will represent the costs of increasing performance in non-large and large cars, respectively, as long as competition prevails in the industry.[18]

Cassella and Rabe's (1978) estimates of the bhp/W coefficients would imply an average cost of increasing acceleration of $75 over the entire GM

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[15]These data were collected by Automated Sciences, Inc. for the DOT National Highway Traffic Safety Administration.

[16]Standard error in parenthesis.

[17]This calculation assumes the other attributes of the car remain the same. Changes in acceleration for a given body are generally accomplished by changes in engines and are accompanied by changes in E and W.

[18]We could again use Lindgren's markup model to determine manufacturing costs. These would be approximately $145 for large and $38 for small and mid-size automobiles.

line, with a cost of $15 for intermediate GM cars and $134 for full-size GM cars. Adjusting these costs to 1978 dollars yields $21 for mid-size and $186 for large automobiles. The authors did not observe statistically significant estimates for small or compact cars or for non-GM products. Our results for small cars compared to those from Charles River Associates are similar as their estimates imply a price effect of about $70 for these cars. In the large or full-size category, the price effect implied by the Charles River Associates estimates is about $90, which is less than one-half of our estimate for these cars. Overall, our estimates of the price-cost of acceleration tend to be somewhat higher than those reported by other investigators.

3.4.4 Weight

In the price equation, the variable "weight" proxies for attributes such as overall size, carrying capacity, quality and comfort.[19] It is interesting to note that the value or price of weight appears to be higher for small and mid-size cars than for large cars. This suggests that weight proxies for a different mix of attributes in large cars. It also may reflect the effect of downsizing on the weight attribute. Specifically, after downsizing, many cars previously classified as large or mid-size would be classified as mid-size or small in our sample. Since the "quality" of a downsized car may be higher per pound than a traditional car, the weight coefficient in small or mid-size cars may be influenced by their inclusion in the category.

One item that should be mentioned at this point concerns the ability to actually estimate separate coefficients for W, E, and A. For a given technology, it would appear that because of the strong relationship between weight and miles per gallon, it should not be possible to obtain independent estimates of all three coefficients. That is, because of the engineering relationship between weight, miles per gallon and performance, one would expect multicollinearity to be a major problem in this estimation. That

[19]Measure of the roominess and length of automobiles were available in the NHTSA data base for some of the observations in our sample. The simple correlations between weight and length and roominess are .87 and .95, respectively for the subsample.

independent estimates can be obtained and that multicollinearity is not a major problem suggests that we are in part estimating the costs of creating E, efficiency, by changing technology. Our data set appears to have captured a snapshot of the system adjusting efficiency not simply by adjusting weight, but also by changing the nature of the car, or, equivalently, employing new technologies to increase efficiency.

3.5 TARGET SETTING

Hedonic price equations such as the one estimated can be used for establishing targets for alternative engine development. Alternative engines - more precisely, automobiles with alternative engines - are simply another method of producing automobiles with desired attributes such as acceleration, fuel economy, comfort, etc. In order to be a viable option, alternative-engined automobiles must be commercially feasibile. That is, a car with an alternative engine such as a Brayton or Stirling must compete, in terms of price, with a conventionally equipped automobile.

As an example of how a hedonic price equation could be used in this context, the results in Table 3.3 were used to price out several of the automobile configurations suggested by JPL in the ATSP/JPL report. Table 3.4 presents the results of applying our equation to the advanced engine configurations given in Table 9-19 (Fuel Economy Projections for Full Size Vehicles) of the ATSP/JPL report. All configurations have 120 bhp and weigh 3500 pounds. For the least desirable advanced engine configuration, the FT metallic Brayton, our estimates suggest that a comparable, conventionally powered automobile would have sold for between $4800 and $4950 in 1978, depending on the manufacturer. An Otto powered automobile with the mileage of the most advanced engine, the ceramic Stirling (24 mpg), would have sold for between $5300 and $5500.

Several aspects of this procedure require elaboration. First, while the attributes of the automobile configurations in Table 3.4 are well within the sample used to estimate our hedonic price equations, other advanced engine vehicles are not. For example, both Brayton configurations in Table 9-20 of the ATSP/JPL report have urban cycle mpgs that exceed the maximum value in our sample. Using hedonic price equations to price out automobiles with attributes much outside the sample employed in estimation may prove problematic. Second, the form of the price equation used in our estimation does not allow for direct interaction between the attribute levels. Potential interaction is, of course, partially controlled by allowing for category specific coefficients, as was done in the estimation reported in Table 3.1. Categories, however, from our perspective, are not an entirely satisfactory method of controlling interaction between absolute levels. Finally, the most unsatisfactory aspect of our hedonic procedure, at least for target setting purposes, is the use of weight as an indicator of all attributes other than performance and fuel economy.

Table 3.4. Automobile Target Prices

Automobile Configuration	1978 Target Price for Automobiles
FT Brayton (metal)	$4808 - 4956
Ft Brayton (ceramic)	$4913 - 5061
SS Brayton (metal)	$4787 - 4935
SS Brayton (ceramic)	$4936 - 5084
Stirling (metal)	$5160 - 5308
Stirling (ceramic)	$5332 - 5480

Equations used to estimate target price were:

(1) $P_{NC} = 1.62W + 74.76E + 2532.38A - 2867$,

(2) $P_C = 1.62W + 74.76E + 2532.38A - 3015$,

where P_{NC} = price for non-Chrysler product and

P_C = price of Chrysler-built automobile.

For studying prices in a cross section or over a short period of time, weight is likely to be an ideal attribute indicator. When setting targets for future automobiles, however, weight may not be a very good indicator of the type of automobile under consideration. As recent "downsizing" efforts by U.S manufacturers have dramatically indicated, technology can change the attribute mix corresponding to any specific weight level. It is unlikely that a 3500 lb Stirling-engined automobile would have the same space and comfort attributes as, say, a 1976 Ford Granada, which also weighs 3500 lbs. Using the weight coefficient to price out the general size and comfort attributes of advanced engined automobiles is problematic.

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SECTION 4.

FUEL CONSUMPTION IMPACTS OF BRAYTON AND STIRLING CYCLE ENGINES

4.1. SUMMARY

A comparison of fuel consumption was performed for the substitution of Brayton and Stirling engines against the Otto cycle baseline engine in cars and light trucks. This substitution was for the vehicle size classes for which there was a clear fuel economy advantage for the advanced engines. A ten-year introduction starting in 1990 and reaching a maximum penetration of 90% of the sales was assumed for turbine engines. A ten-year introduction starting in 1995 and also reaching 90% of sales was assumed for Stirling engines.

Under these assumptions, an improvement over the Otto cycle baseline for the maximum achievable domestic CAFE (using a projected 1985 sales mix) was found to range from 14 percent for the metallic Brayton to 34 percent for the ceramic Stirling as presented in Table 4.1.

Table 4.1. CAFE Improvement

Engine Technology	Maximum CAFE	% Improvement over Baseline
Otto	32.1	--
Metallic Brayton	36.7	14%
Ceramic Brayton	40.2	25%
Metallic Stirling	41.6	29.5%
Ceramic Stirling	43.1	34%

The substitution of these advanced engines for the Otto cycle baseline engine would yield a maximum yearly savings of up to 1.62 quads (10^{15} Btu) per year of petroleum as summarized in Table 4.2.

Table 4.2 Maximum Yearly Quad Savings

Engine Technology	Quads Saved over Baseline	% Improvement over Baseline
Otto	-	-
Metallic Brayton	0.83	10.9%
Ceramic Brayton	1.21	22.0%
Metallic Stirling	1.28	17.3%
Ceramic Stirling	1.62	24.5

One economic measure of the value of the petroleum conservation potential of these advanced engine technologies is the present value of the future dollar savings due to the reduction in petroleum consumption from the Otto cycle baseline. The DRI long-term projections for motor fuel prices are presented in Figure 4.1. Using these projections and a 10 percent rate of discount, the maximum yearly savings were found to reach the following values:

Table 4.3 Present Value of Maximum Yearly Savings

Engine Technology	Present Value of Maximum Yearly Savings Billion Dollars
Metallic Brayton	1.4
Ceramic Brayton	2.4
Metallic Stirling	1.6
Ceramic Stirling	2.3

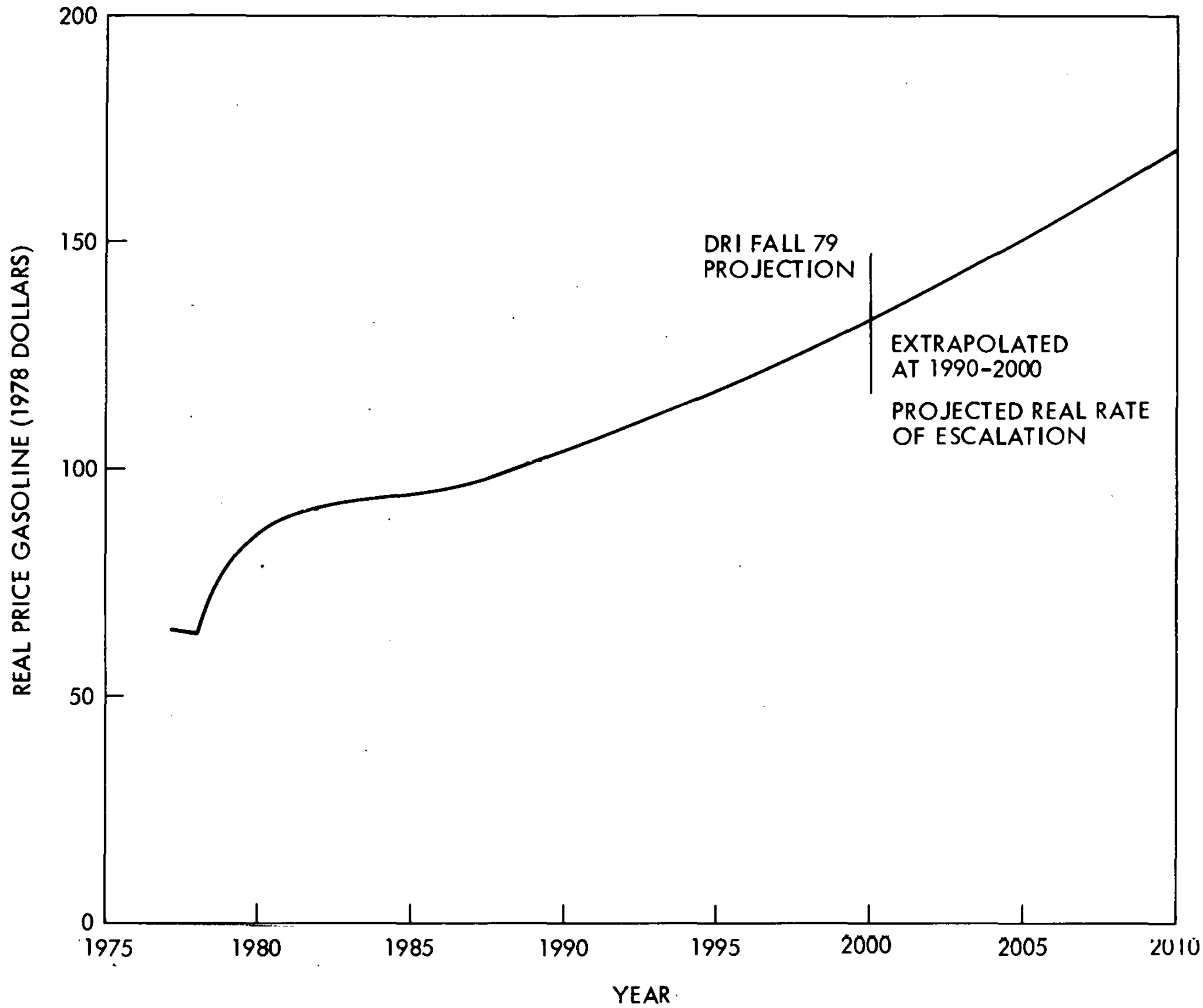

Figure 4.1. Fuel Price Projections

The total present value of the potential future savings are approximately estimated to be:

Table 4.4. Total Present Value of Petroleum Savings

Engine Technology	Present Value of Future Savings Billion Dollars
Metallic Brayton	20.1
Ceramic Brayton	36.3
Metallic Stirling	16.9
Ceramic Stirling	22.7

4.2 OBJECTIVES

The principle objective of this task was to provide a comparative evaluation of metallic free-turbine Brayton, ceramic free-turbine Brayton, metallic Stirling, and ceramic Stirling against a naturally aspirated, uniform charge, Otto cycle baseline. This will be done in terms of corporate average fuel efficiency, yearly petroleum use, and the present value of the future petroleum savings.

4.3. METHODOLOGY

4.3.1 Establishment of the Otto Cycle Base Line

The uniform charge, naturally aspirated, Otto cycle engine is the current dominant automotive engine technology. Within the current sales fleet are also found turbo-charged Otto, naturally aspirated Diesel and turbo-charged Diesel. Each of these engines can potentially provide a fuel efficiency improvement over the uniform charged, naturally aspirated Otto.

Historically, the uniform charge, naturally aspirated Otto (with the minor exception of a few specialty cars) was the unanimous choice of the domestic manufacturers due to relatively low production cost and the insensitivity of purchasers to the social cost of emissions and petroleum consumption. The attempts to internalize such external social costs by the

Congress through regulation of corporate average fuel economy (in addition to emissions regulations) has fostered the introduction of more costly but more fuel efficient conventional alternatives to the naturally aspirated, uniform charge Otto engine.

The underlining presumption of this analysis is that the alternative engine's (Brayton and Stirling) research and development program has been successful and they have joined the conventional engines on the producer's "shopping list" of more fuel efficient alternatives to the Otto engine. Rather than presume a level of fuel economy regulation and an "optimal" mix of the various conventional alternatives and then compare the Brayton and Stirling by differentially substituting for one or more of these engines, a "pure" Otto baseline was established and the alternative engines singularly substituted if they held a clear fuel economy advantage. The comparative analysis for the conventional alternatives has not been performed for this analysis.

1977 published EPA fuel economy data was used to establish the inertial weight versus fuel economy curve for the Otto cycle baseline. The potential weight reductions from 1977 to 1985 for 1977 baseline inertial weights were derived from a DOT analysis (Reference 3) and are presented in Figure 4.2. The maximum weight reduction potential was assumed to be achieved in the ensuing ten years (by 1995) and the value of this reduction was that previously published in the JPL analysis Should We Have a New Engine. (This is also in close agreement to the Series II weight reduction potential values established by the Federal Task Force on Motor Vehicle Goals Beyond 1980.)

The potential fuel economy improvements at a constant inertia weight between current and 1985 uniform charge Otto engines were projected in a recent JPL report (Reference 4). The percentage improvement implicit in this data was used to proportionately scale the 1977 EPA baseline to a projected 1985 fuel economy versus inertial weight curve.

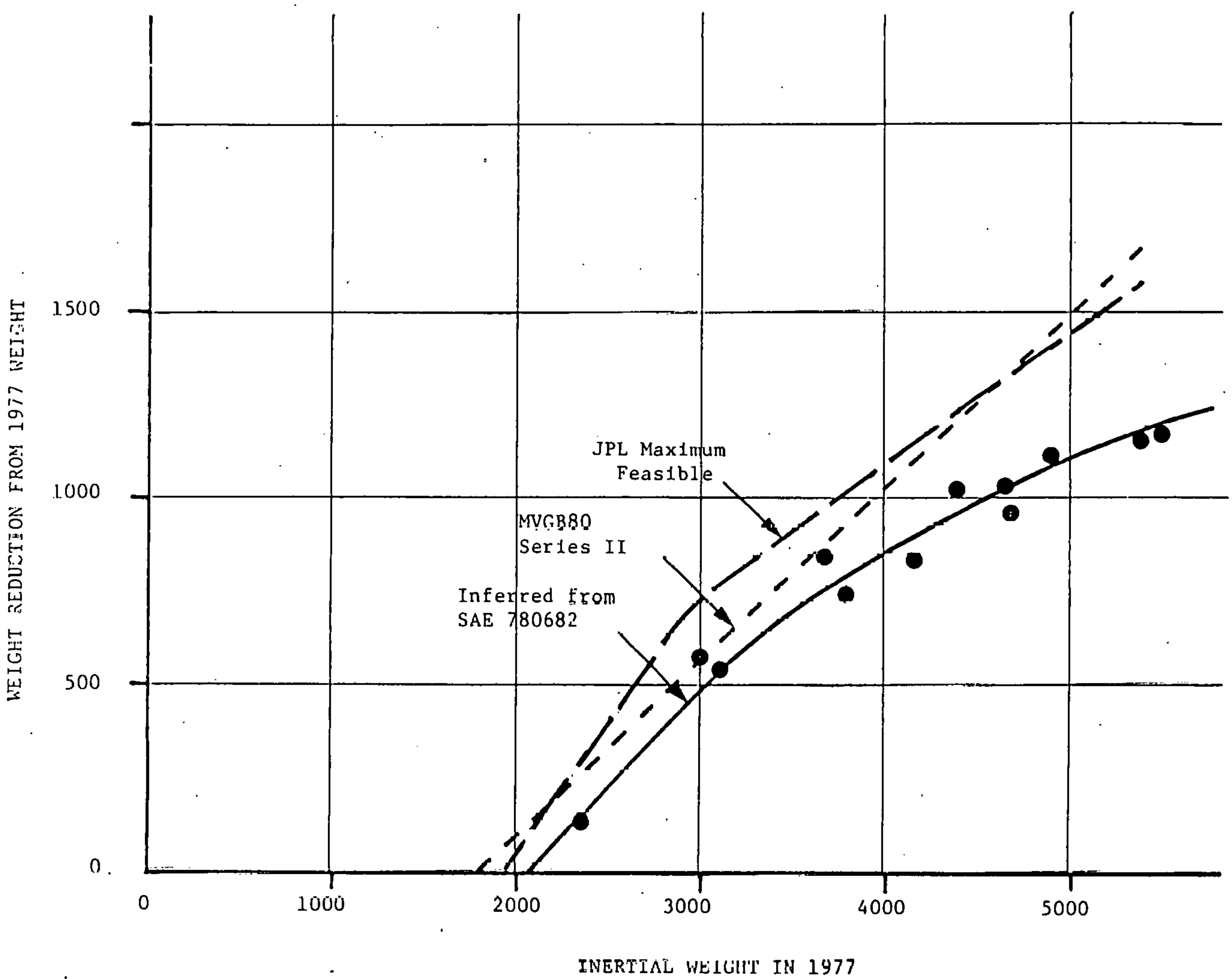

Figure 4.2. Potential Weight Reductions

Technological progress seldom comes to an abrupt halt, especially if there exists regulatory pressures for change. By 1985, currently known technologies such as turbo charging and electronic engine control will not yet be fully applied across the domestic sales mix. For the ten years between 1985 and 1995, it was therefore assumed that the improvement in the fuel economy versus inertial weight curves would be 1/2 that projected for 1977-1985. Beyond 1995, no change in weights or fuel economies were assumed for the vehicles.

4.3.1.1 Sales Mix

Under the assumption of compliance by the domestic manufacturers to the Energy Policy Conservation Act of 1975 (Public Law 94-163), the sales mix was then adjusted to meet the statutory schedule of:

Year	CAFE
1978	18
1979	19
1980	20
1981	22
1982	24
1983	26
1984	27
1985	27.5

As follows:

Year		Small	Subcompact	Compact	Mid	Large
1977	domestics + imports	7	6	16	39	32
	domestics only	1	3	12	37	31
1978	domestics + imports	7	6	16	39	32
	domestics only	1	3	12	37	31
1979	domestics + imports	8	7	16	38	31
	domestics only	2	4	12	36	30
1980	domestics + imports	7	9	17	38	29
	domestics only	2	6	13	35	28
1981	domestics + imports	8	11	19	36	26
	domestics only	3	8	15	33	25
1982	domestics + imports	8	3	22	34	23
	domestics only	4	10	18	30	22
1983	domestics + imports	8	15	28	29	20
	domestics only	4	12	23	24	19
1984	domestics + imports	8	3	22	34	23
	domestics only	4	11	18	30	20
1985-	domestics + imports	8	10	19	36	26
2010	domestics only	4	8	15	33	25

While the 1985 sales mix under the above technology assumptions differs only moderately from the 1977 mix, the mix for 1982 through 1984 appears to differ markedly. This is an artifice of the petroleum consumption model used which causes fuel economy improvements to change linearly between 1977 and 1985. The rapid fuel economy improvements (two mpg per year) required by statute must, in this model, be accomodated by changing the sales mix. In reality, one would expect that weight and propulsion technology would be used to minimize rapid changes in sales mix.

Consistent with the purpose of comparing the technological potential of the advanced alternative engines to an Otto cycle baseline, the sales mix which permitted compliance to be met in 1985 was held constant until the year 2010.

4.3.1.2. Fleet Size Calculations

The total number of cars in the fleet and new cars sold each year from 1977 to the year 2010 is input to the model. The scrappage rate of old cars was adjusted from year to year depending on new car sales and on the total fleet size projections by increasing or decreasing the survival probability of cars 8 to 12 years old. The resulting implicit fleet retirement rate is shown in Figure 4.3.

4.3.1.3. Miles Driver per Vehicle

The total number of miles driven each year from 1977 to the year 2010 is an input into the model. The number of miles driven for a given vehicle can depend on its age, weight class, and the type of engine.

4.3.1.4. Fuel Consumption

The fuel economy for each automobile is assumed to remain constant throughout its lifetime. The highway and urban fuel economy are averaged under the assumption that 55 percent of the driving is done in an urban area.

The total fuel consumption is calculated from the fuel economy and number of miles driven for each car. Since this method of estimation has underestimated fuel consumption when compared to historical data, this estimate is multiplied by 1.15 for fuel consumption by cars produced in model years earlier than 1977.

4.3.1.5. Corporate Average Fuel Economy

The corporate average fuel economy is calculated each year using the fuel economy test figures and the sales mix for domestically produced automobiles.

4.3.2 Advanced Alternative Engines

To assess the comparative fuel use impacts of the Brayton and Stirling engines the following assumptions were made.

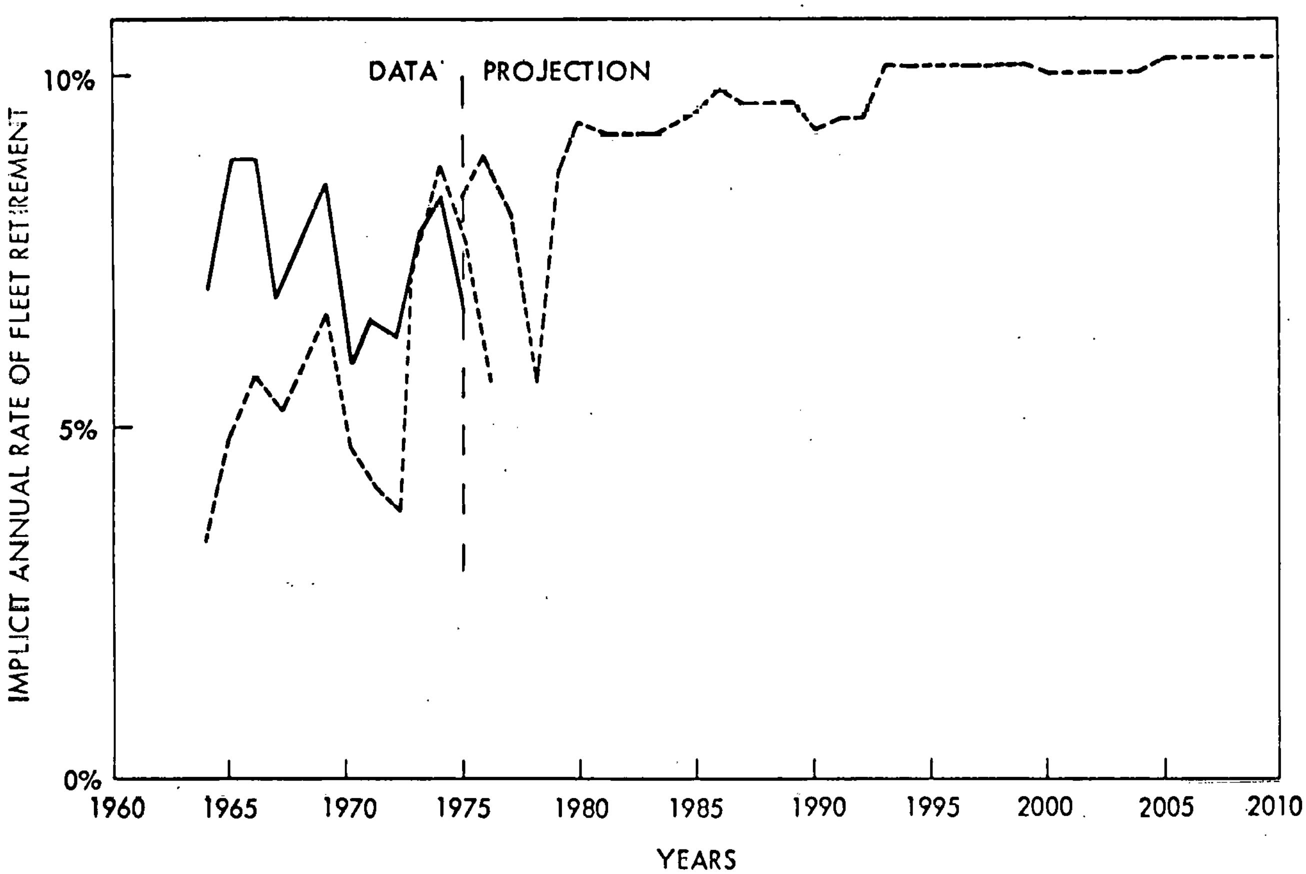

Figure 4.3. Annual Fleet Retirement Rate

1. A span of 10 years would be used between the first commercial introduction and maximum level of production for all engines. This represents a conversional replacement of two to three production modules (400K units a year for a module) per year.

2. Brayton engines would be ready for commercial introduction in 1990 in either ceramic or metallic versions.

3. Stirling engines would be five years behind Brayton engines in commercial readiness.

The fuel economy of the advanced engines was derived from the projections made in a recent JPL report (Reference 4). From this data, a curve of gasoline equivalent composite EPA fuel economy versus Otto engine equivalent inertial weight was derived. The Otto engine equivalent inertial weight is the inertial weight of the performance equivalent Otto cycle powered vehicle, hence the true inertial weight can be appreciably less. Likewise, the fuel consumption at the pump of an alternative engine using a fuel other than gasoline can be markedly different from the gasoline equivalent consumption.

Adjustments were made for the slight difference in the baseline fuel economies used in the JPL ATSP report and the baseline fuel economy used in this analysis. The proportional difference between the ATSP baseline and the baseline used in this analysis was applied to the ATSP advanced engine results. The dates associated with these derived fuel economy versus inertial weight curves were taken to be 1990 for the Brayton engines and 1995 for the Stirling engines.

As with the Otto cycle baseline, it is unrealistic to assume that a technology once introduced will not experience some degree of improvement. Hence, it was assumed that the advanced engines would experience the same degree of proportional improvement for the same period of time as the baseline Otto cycle engine experienced. Since one would expect that a newly introduced technology would have a greater improvement potential than a mature technology this appears to be a conservative assumption.

The weight reduction potential of the vehicles with the advanced engines was taken to be the same as that assumed for the baseline Otto cycle vehicles. The weight reduction potential is a function of true inertial weight and not Otto engine equivalent inertial weight. For those engines for which the true inertial weight is significantly less than the Otto equivalent inertial weight (Brayton), a slight overestimate in weight reduction potential would be expected.

4.4 ASSUMPTIONS AND DATA

The introduction of advanced engines was analyzed by estimating the impact of these engines on total fuel consumption and corporate average fuel economy. The analysis utilized a simple "bookkeeping" computer model of the fleet of cars in the United States from 1977 to the year 2000. The following is a description of the assumptions made for this analysis and the data that was used.

4.4.1 Fleet Characteristics

4.4.1.1 Total Fleet Size and Number of New Cars

	Total Passenger Cars $X10^6$	New Car Sales $X10^6$
1975	95.24	10.48
1976	97.82	10.76
1977	99.90	10.99
1978	102.86	11.31
1979	108.34	11.92
1980	110.95	12.20
1981	112.92	12.42
1982	114.91	12.64
1983	116.92	12.86
1984	118.96	13.08
1985	120.96	13.30
1986	122.81	13.51
1987	124.20	13.66
1988	125.82	13.84
1989	127.52	14.03
1990	129.17	14.21
1991	131.35	14.45
1992	133.46	14.68
1993	135.57	14.91
1994	136.63	15.03
1995	137.68	15.15

1996	138.74	15.26
1997	139.79	15.78
1998	140.85	15.49
1999	141.90	15.61
2000	142.96	15.73
2001	144.17	15.86
2002	145.39	15.99
2003	146.62	16.13
2004	147.86	16.26
2005	149.11	16.40
2006	150.17	16.52
2007	151.24	16.64
2008	152.31	16.75
2009	153.39	16.87
2010	154.48	16.99

4.4.1.2 Age Distribution of the 1977 Fleet

Age	Number (1000s)
1 (new)	9756[a]
2	7683[a]
3	9746[b]
4	11130
5	9872
6	8249
7	7966
8	7774
9	6856
10	5361
11	4888
12	3923
13	2578
14	1740
15	1083
16 and greater	526
Total	99131

a. Automotive News, 1978 Market Data Book.

b. The number of old cars in 1977 was derived from the age distribution in 1976 as published in Automotive News, 1978 Market Data Book.

4.4.1.3 Production Mix

4.4.1.3.1 By weight class

The following table displays the percent of sales attributable to domestics and imports.

Year		Small	Subcompact	Compact	Full	Large
1977	domestics + imports	7	6	16	39	32
	domestics only	1	3	12	37	31
1978	domestics + imports	7	6	16	39	32
	domestics only	1	3	12	37	31
1979	domestics + imports	8	7	16	38	31
	domestics only	2	4	12	36	30
1980	domestics + imports	7	9	17	38	29
	domestics only	2	6	13	35	28
1981	domestics + imports	8	11	19	36	26
	domestics only	3	8	15	33	25
1982	domestics + imports	8	13	22	34	23
	domestics only	4	10	18	30	22
1983	domestics + imports	8	15	28	29	20
	domestics only	4	12	23	24	19
1984	domestics + imports	8	13	22	34	23
	domestics only	4	11	18	30	21
1985-	domestics + imports	8	11	19	36	26
2000	domestics only	4	8	15	33	25

4.4.1.3.2 By engine type

The following table displays the percent of sales in a given weight class for an advanced engine that is in full production. The remainder of sales in that weight class will be for the Otto engine.

Engine	Small	Subcompact	Compact	Full	Large
Metallic Brayton	0	50	90	90	90
Ceramic Brayton	90	90	90	90	90
Metallic Stirling	90	90	90	90	90
Ceramic Stirling	90	90	90	90	90

4.4.1.3.3 Introduction of advanced engines.

Engine	Year Engine Is First Introduced	Year Engine Is at Max. Production
Metallic Brayton	1990	2006
Ceramic Brayton	1990	2006
Metallic Stirling	1995	2005
Ceramic Stirling	1995	2005

4.4.1.3.4 Scrappage.

Age	Probability of Scrappage in Next Year
0-1	.002[a]
1-2	.005
2-3	.011
3-4	.020
4-5	.034
5-6	.064
6-7	.102
7-8	.157
8-9	.215
9-10	.260
10-11	.289
over 11	.300

[a]D.B. Shonka, A.S. Loebel, and P.O. Patterson, Transportation Energy Conservation Book, Edition II, Table 1-55, October 1977, Oak Ridge National Laboratory.

4.4.2 Miles Driven

4.4.2.1 Total Miles

Year	Total Miles (billions)
1977	1.1161
1978	1.1441
1979	1.1727
1980	1.2017
1981	1.2248
1982	1.2480
1983	1.2717
1984	1.2954
1985	1.3194
1986	1.3420
1987	1.3598
1988	1.3802
1989	1.4012
1990	1.4223
1991	1.4460
1992	1.4660
1993	1.4870
1994	1.5070
1995	1.5280
1996	1.5480
1997	1.5690
1998	1.5890
1999	1.6100
2000	1.6300

4.4.2.2 Miles Driven per Vehicle

Age	Engine	Weight[a] Classes 1-3	Weight[a] Class 4	Weight[a] Classes 5&6	Overall[b]
1 (new)	Otto	19080	16740	17640	18000
2		16060	14043	14798	15100
3		14204	12462	13132	13400
4		12932	11346	11956	12200
5		11978	10509	11074	11300
6		11300	9765	10290	10500
7		10494	9207	9702	9900
8		9858	8649	9114	9300
9		9328	8184	8624	8800
10		8904	7812	8232	8400
11		8480	7440	7840	8000
12		8056	7068	7448	7600
13		7738	6789	7154	7300
14		7420	6510	6860	7000
15		7102	6231	6566	6700
16		7102	6234	6566	6700

[a]Derived from overall average using data for miles driven by weight class, Shonka, D.B., Loebl, A.S., and Patterson, P.D., Transportation Energy Conservation Data Book, Edition II, Table 1-44, October 1977, Oak Ridge National Laboratory.

[b]Tables 1-55 from above reference.

4.4.3 Fuel Economy Data

4.4.3.1 Historical Fuel Economy

Model Year	Urban (mpg)	Highway (mpg)
1976	14.8[a]	21.0[a]
1975	13.1[a]	18.6[a]
1974	12.08[b]	17.15[c]
1973	12.35	17.54
1972	12.73	18.08
1971	12.92	18.35
1970	13.24	18.80
1969	12.92	18.35
1968	13.16	18.69
1967	13.61	19.33
1966	13.70	19.45
1965	13.73	19.50
1964	14.27	20.26
1963	13.35	18.96
1962	14.77	20.97
1961	14.34	20.36
1960	14.13	20.06

[a]Derived from Table 2 in "Automotive Fuel Economy Program," Second Annual Report to The Congress, National Highway Traffic Safety Administration, Office of Automotive Fuel Economy, January 1978.

[b]1972 FTP data was obtained from "A Report on Automobile Fuel Economy," U.S. Environmental Protection Agency, Office of Air and Water Programs, Office of Mobile Source Air Pollution Control, October 1973, p. 33. Data based on 1972 FTP results.

To correct 72 FTP data to 75 FTP data, a correction factor of 1.058 was applied (e.g. Data x 1.058 = Urban). Austin, T.C. and Hellman, K.H., "Fuel Economy of the 1975 Models," SAE paper 740970, October 1974, p. 18.

[c]Highway numbers are derived from the urban by multiplying by 1.42.

4.4.3.2 Otto Engine Fuel Economy

Year	Small	Subcompact	Compact	Full	Large
1977[a]	32.1	28.7	24.4	18.2	14.3
1985	39.0	35.5	33.0	28.5	22.0
1995	42.0	39.0	37.0	33.5	26.0

4.4.3.3 Metallic Brayton Fuel Economy

Year	Small	Subcompact	Compact	Full	Large
1985	38.0	37.2	36.2	34.5	29.8
1995	41.8	40.9	39.8	38.0	32.8

4.4.3.4 Ceramic Brayton Fuel Economy

Year	Small	Subcompact	Compact	Full	Large
1990	45.0	43.6	42.5	40.0	35.3
1995	47.2	45.8	44.6	42.0	37.1

4.4.3.5 Metallic Stirling Fuel Economy

Year	Small	Subcompact	Compact	Full	Large
1985	46.7	45.2	43.0	38.4	30.0
1995	51.4	49.7	47.3	42.2	33.0

4.4.3.6 Ceramic Stirling Fuel Economy

Year	Small	Subcompact	Compact	Full	Large
1990	55.5	52.0	48.2	43.0	36.8
1995	58.3	54.6	50.6	45.2	38.6

[a] Shonka D.B., Loebel, A.S., and Patterson, P.D., Transportation Energy Conservation Data Book, Edition II, Table 2-19, October 1977, Oak Ridge National Laboratory.

4.4.4 Light Truck Data and Assumptions

4.4.4.1 Light Truck Populations

Year	Light Trucks
1965	9.845
70	13.265
75	18.96
80	21.84
85	24.81
90	26.13
95	29.40
00	32.47
05	33.86
10	35.08

4.4.4.2 Light Truck Average Annual VMT, Market and VMT Share

Vehicle Age (Years)	Average VMT (1000 miles)	Market Share (%)	VMT Share (%)
1	15.2	7.0	10.1
1 - 2	15.8	9.7	14.6
2 - 3	14.9	9.2	13.0
3 - 4	13.0	8.7	10.8
4 - 5	11.7	8.0	8.9
5 - 6	10.8	7.1	7.3
6 - 7	10.1	6.3	6.0
7 - 8	9.5	5.6	5.0
8 - 9	8.9	5.1	4.3
9 - 10	8.3	4.6	3.6
10 - 11	7.8	4.1	3.0
11 - 12	7.3	3.6	2.5
12 - 13	6.7	3.2	2.0
13 - 14	6.2	2.8	1.6
14 - 15	5.8	2.5	1.4
15 - 16	5.4	2.2	1.1
16	4.9	10.3	4.8
Total		100.0	100.0

4.4.4.3 Otto Cycle Fuel Economy

Year	New Vehicle EPA Composit mpg	Total Fleet VMT Weighted on-road mpg
1970	10.6	10.5
1975	10.9	10.1
1980	15.1	11.5
1985	20.1	13.8
1990	21.3	15.9
1995	22.3	17.5
2000	23.2	18.6
2005	23.2	19.1
2010	23.2	19.2

4.4.4.4 Alternative Engine Light Truck Fuel Efficiency

	New Vehicle		EPA Composit mpg	
Year	Metallic Brayton	Ceramic Brayton	Metallic Stirling	Ceramic Stirling
1970	NA	NA	NA	NA
1975	NA	NA	NA	NA
1980	NA	NA	NA	NA
1985	NA	NA	NA	NA
1990	27.7	31.3	NA	NA
1995	28.1	31.8	28.3	33.1
2000	28.1	31.8	28.3	33.1
2005	28.1	31.8	28.3	33.1
2010	28.1	31.8	28.3	33.1

4.5. RESULTS OF THE ANALYSIS

The results of this analysis are graphically presented in the six following sections. These sections are:

(1) Otto cycle baseline (4.5.1)
(2) Metallic free turbine Brayton (4.5.2)
(3) Ceramic free turbine Brayton (4.5.3)
(4) Metallic Stirling (4.5.4)
(5) Ceramic Stirling (4.5.5)

Each of these sections contain the following:

1. The presumed relationships between the Otto engine equivalent inertial weight and the gasoline equivalent fuel efficiency between 1977 and 1995.

2. The assumptions of total sales, volume of each sales class and the percent penetration of each alternative engine.

3. The corporate average fuel economy which would be achieved given the above assumptions.

4. The total impact upon petroleum consumption in quads.

The two following figures present:

1. The impact on petroleum conservation in terms of quads per year versus year for the four alternative engines as savings over the Otto cycle baseline.

2. The second figure presents the discounted present value at $13.50 per barrel of petroleum and a ten percent rate of discount for the petroleum savings for each year for the four advanced engines.

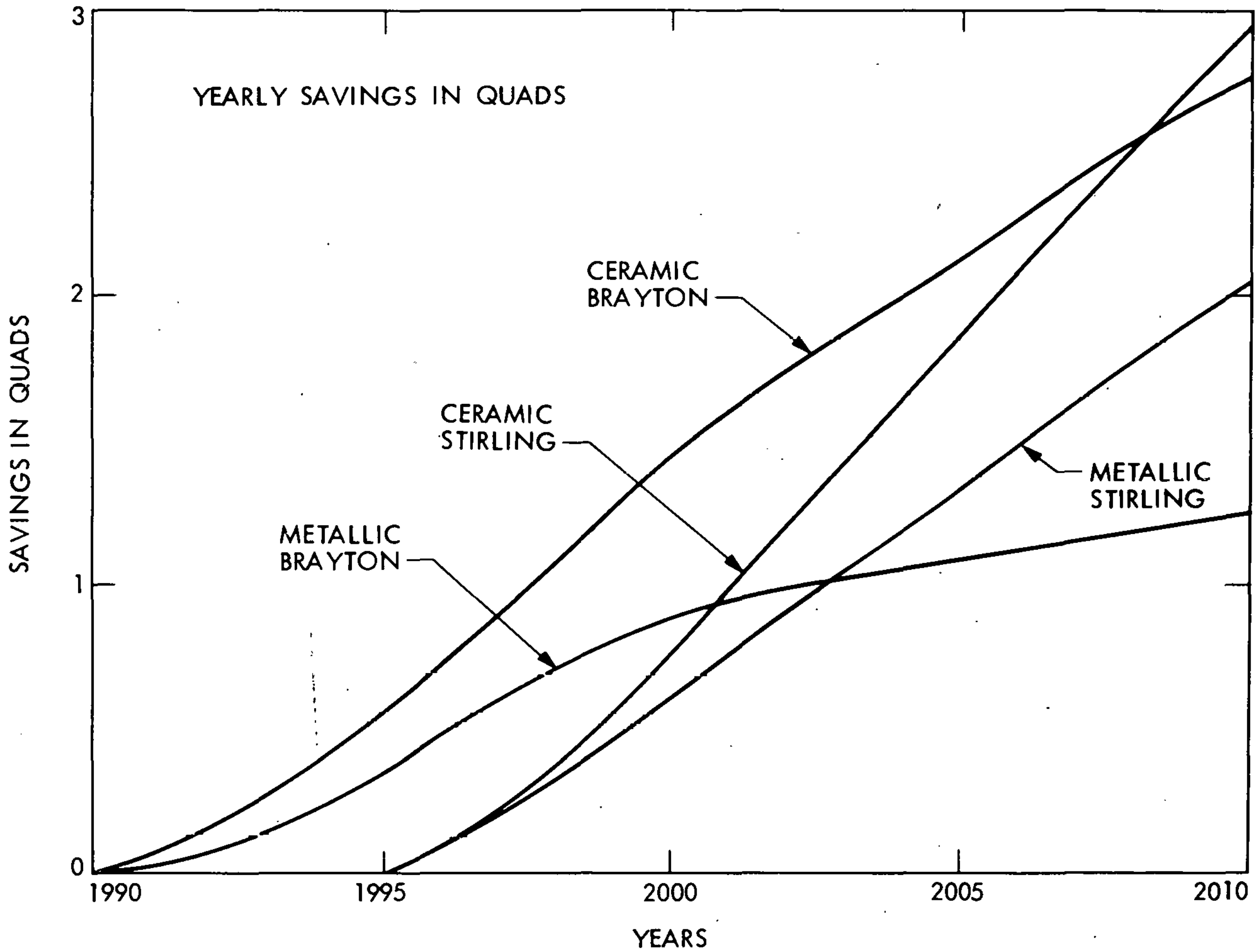

Figure 4.4. Potential Savings of Petroleum from Advanced Engines

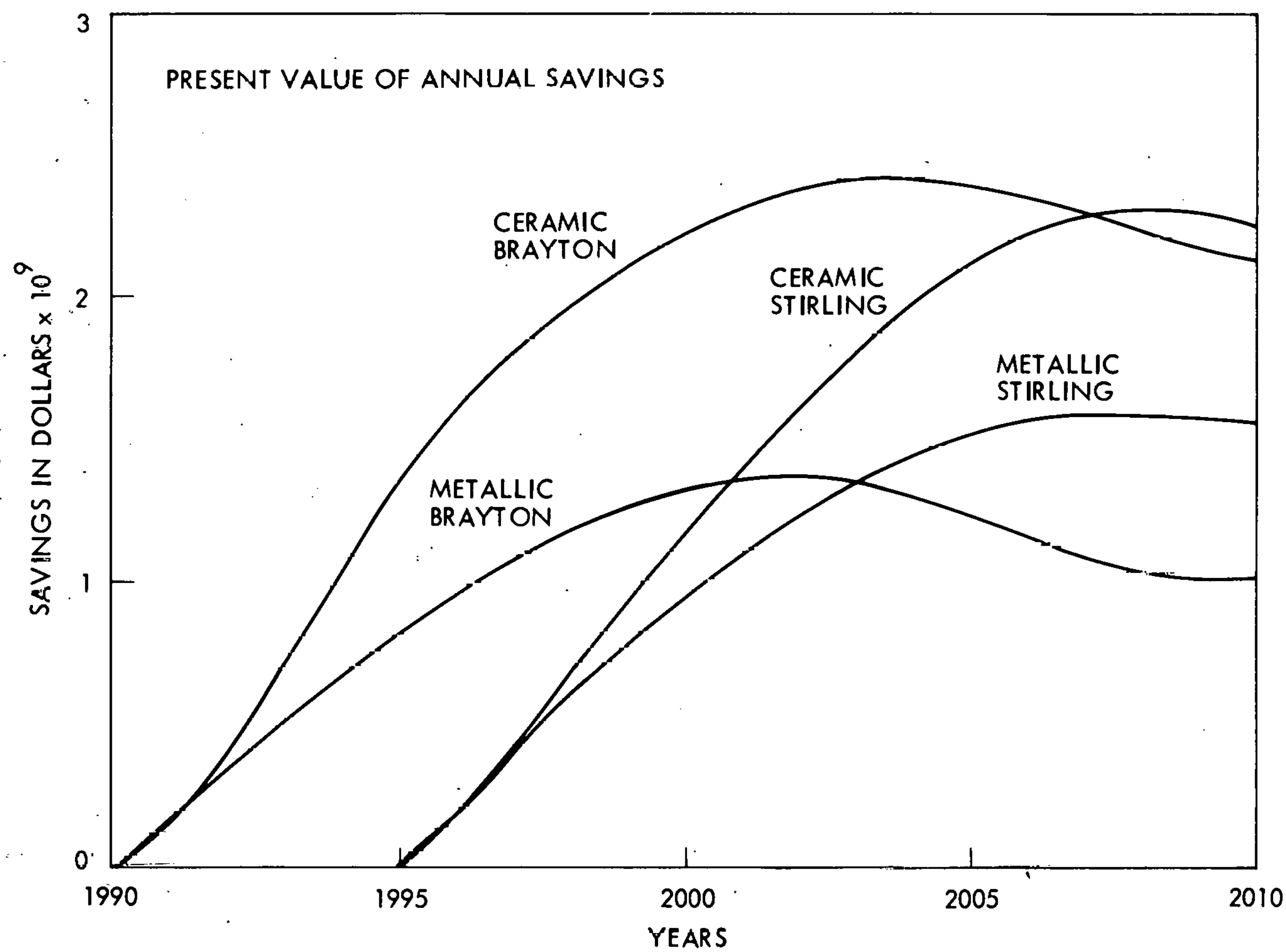

Figure 4.5. Present Value of Potential Dollar Savings from Advanced Engines

4.5.1 OTTO CYCLE BASELINE

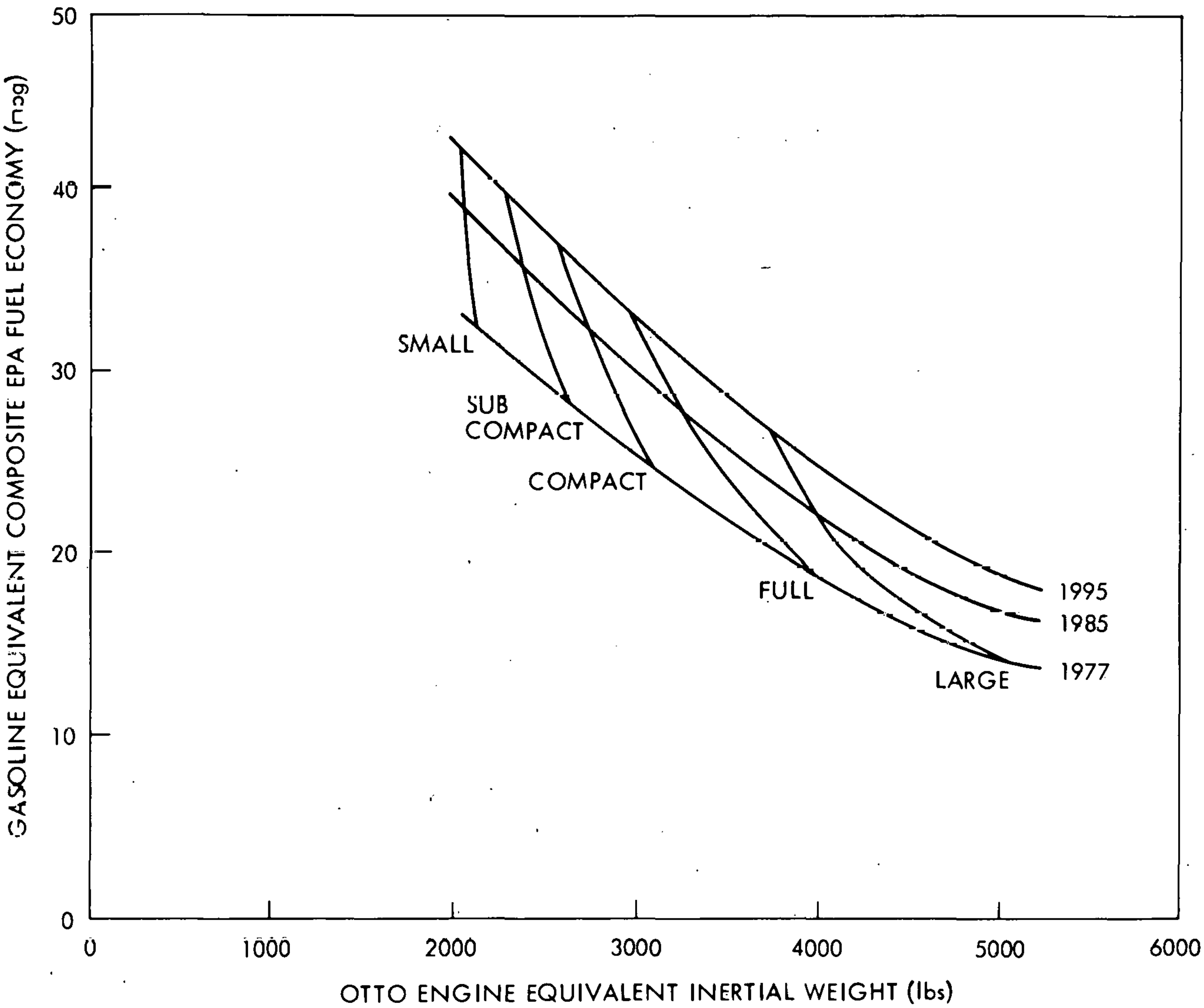

Figure 4.6. Fuel Efficiency vs. Inertial Weight of Otto Cycle Engines

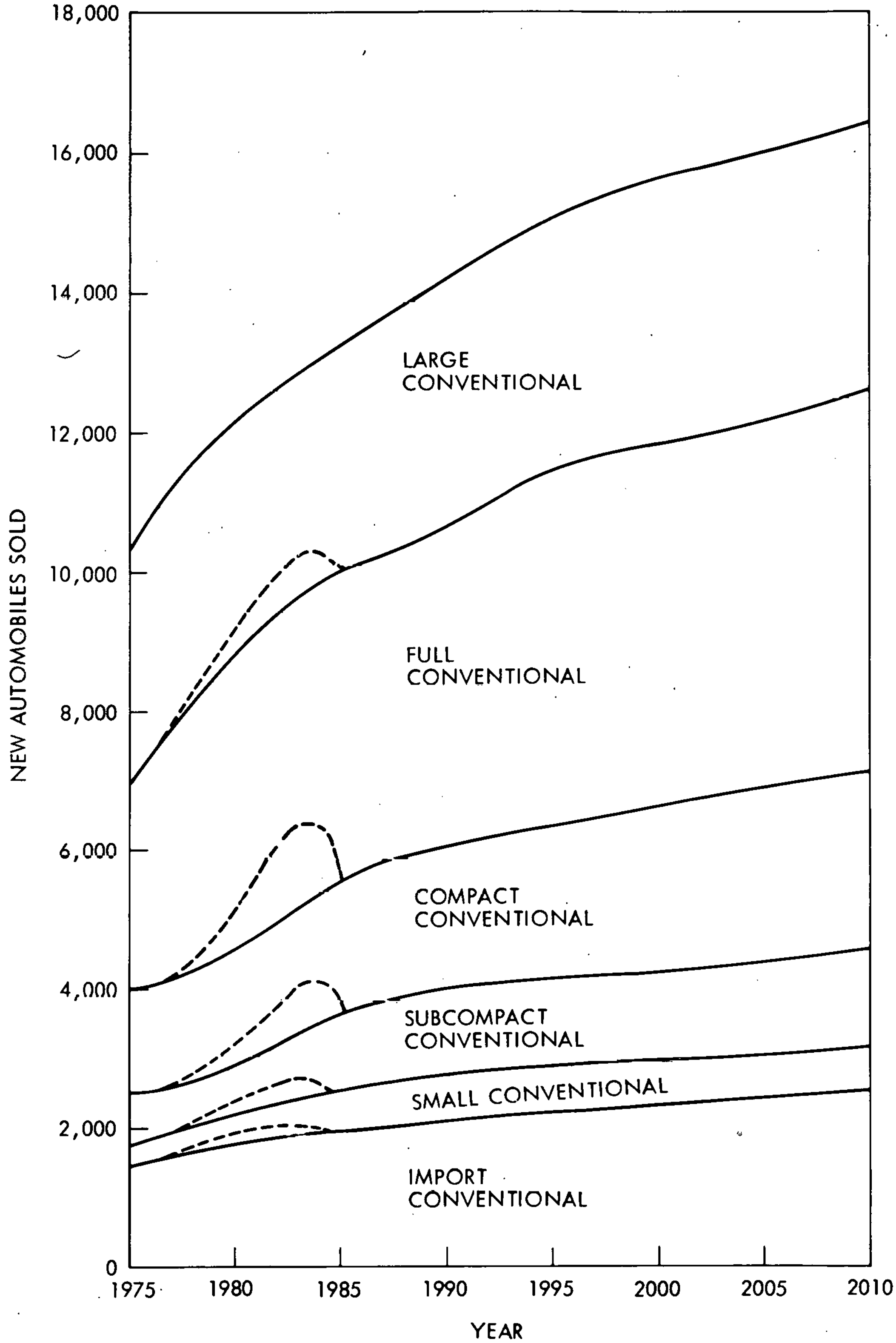

Figure. 4.7. Future Fleet Size with Otto Cycle Engines

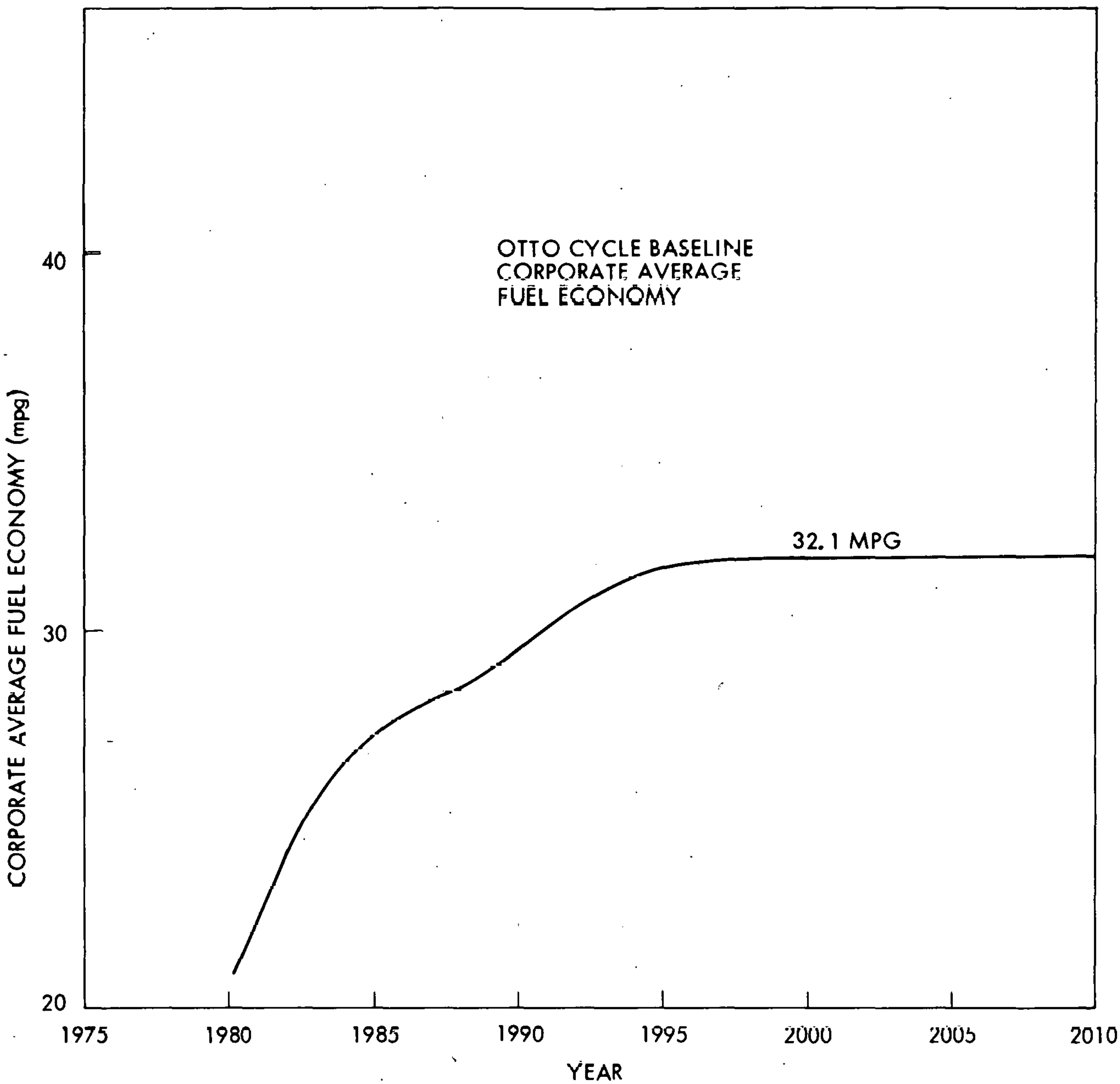

Figure 4.8. CAFE with Otto Cycle Engines

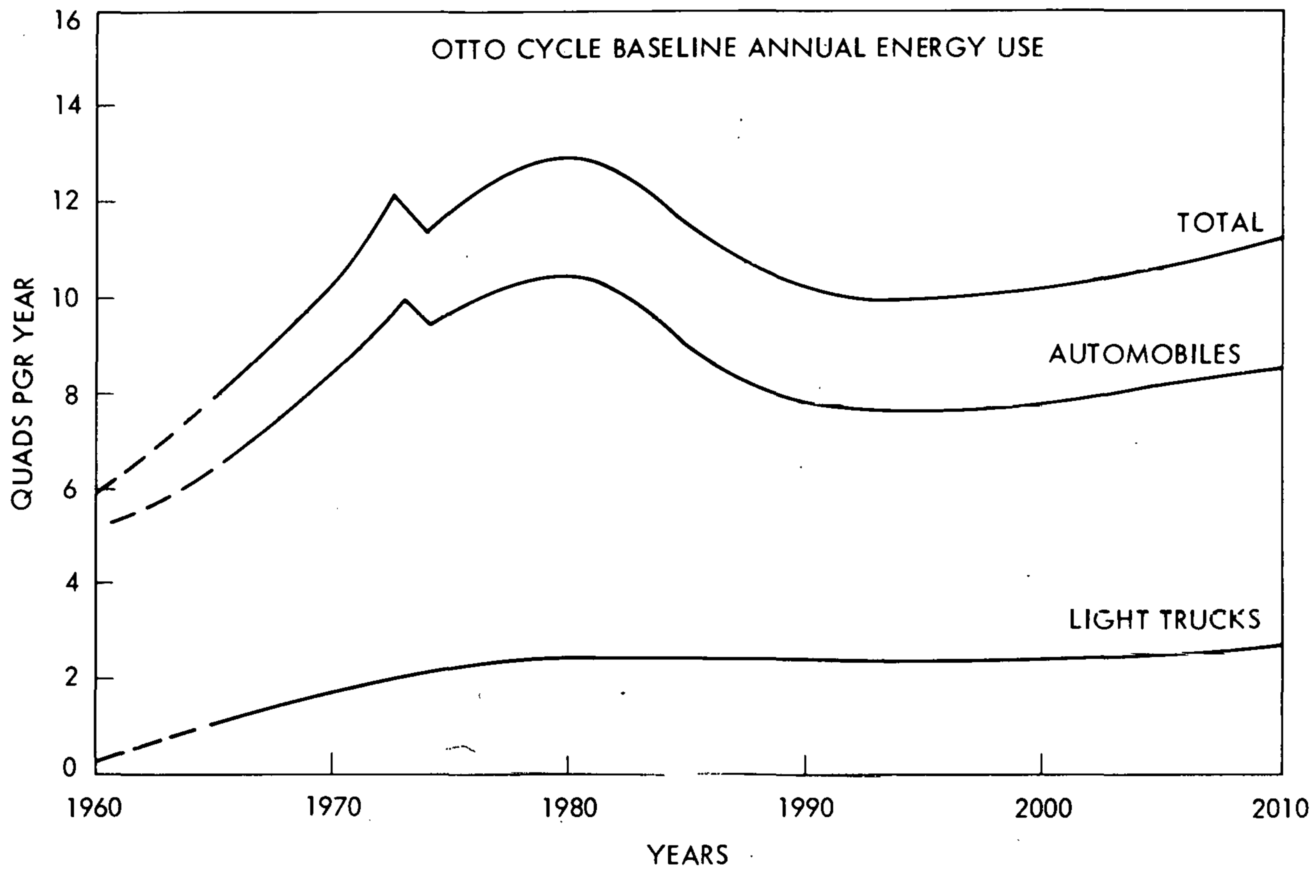

Figure 4.9. Fuel Consumption with Otto Cycle Engines

4.5.2 METALLIC BRAYTON

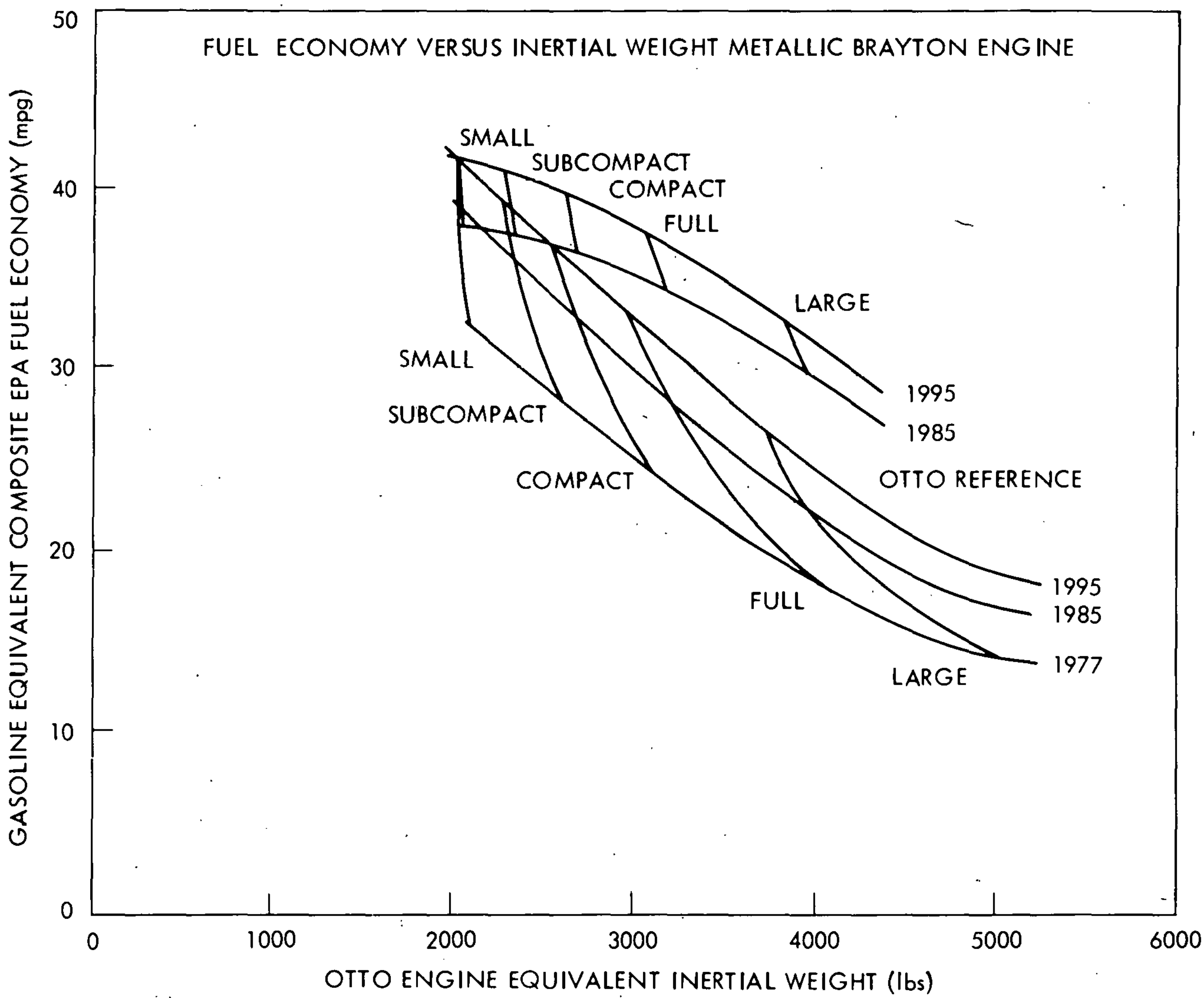

Figure 4.10. Fuel Efficiency vs. Inertial Weight of Metallic Brayton Cycle Engines

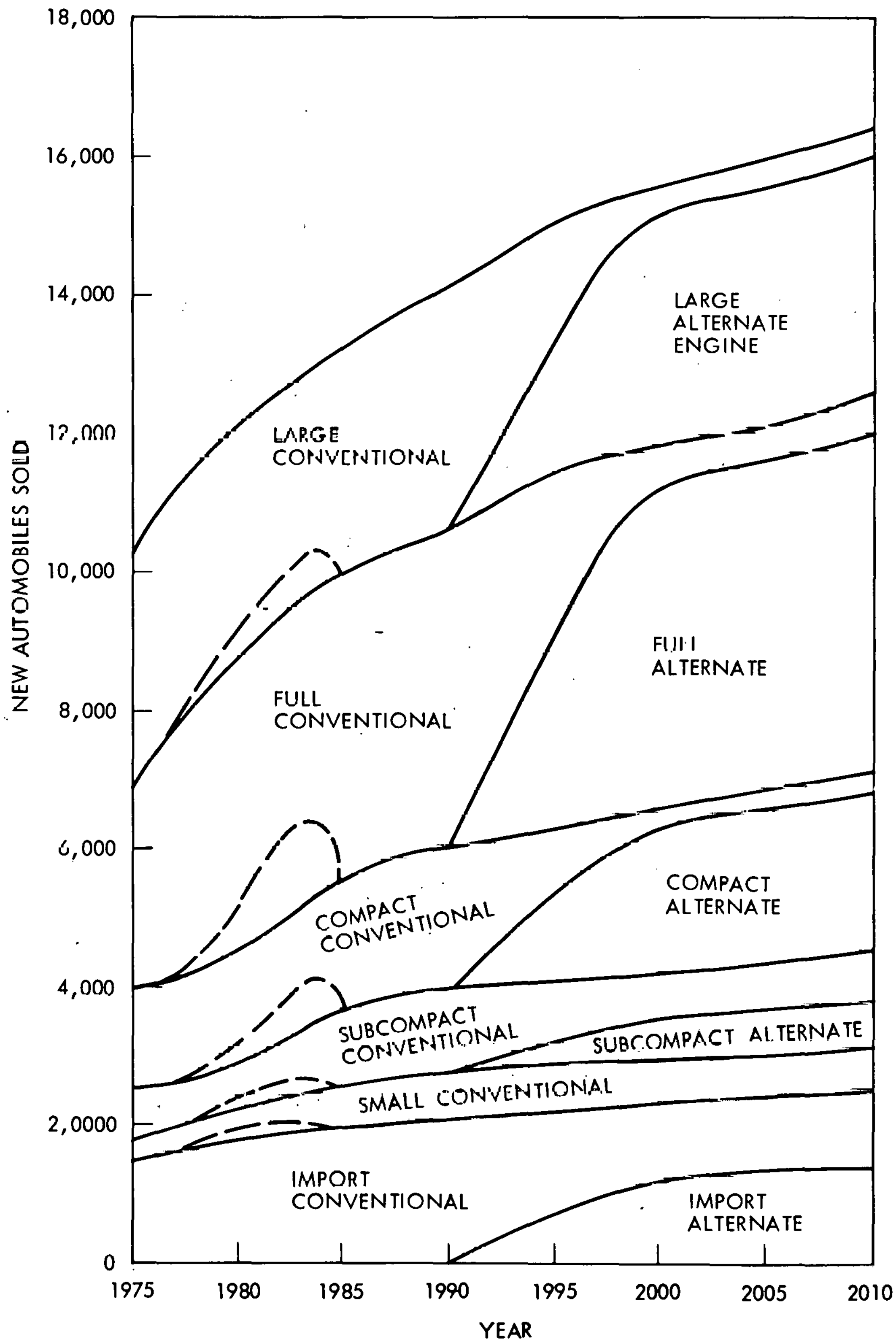

Figure 4.11. Future Fleet Size with Metallic Brayton Cycle Engines

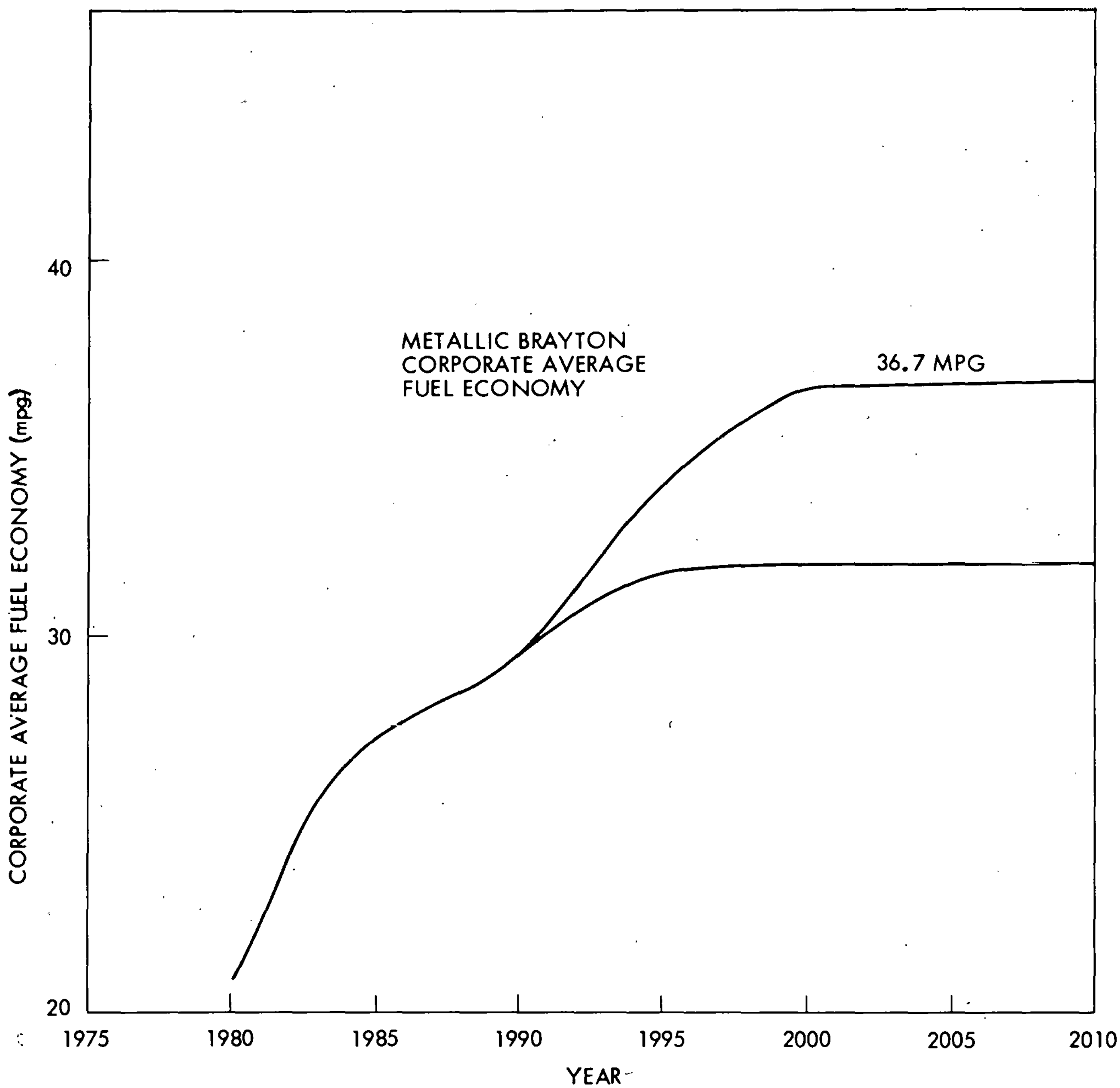

Figure 4.12. CAFE with Metallic Brayton Cycle Engines

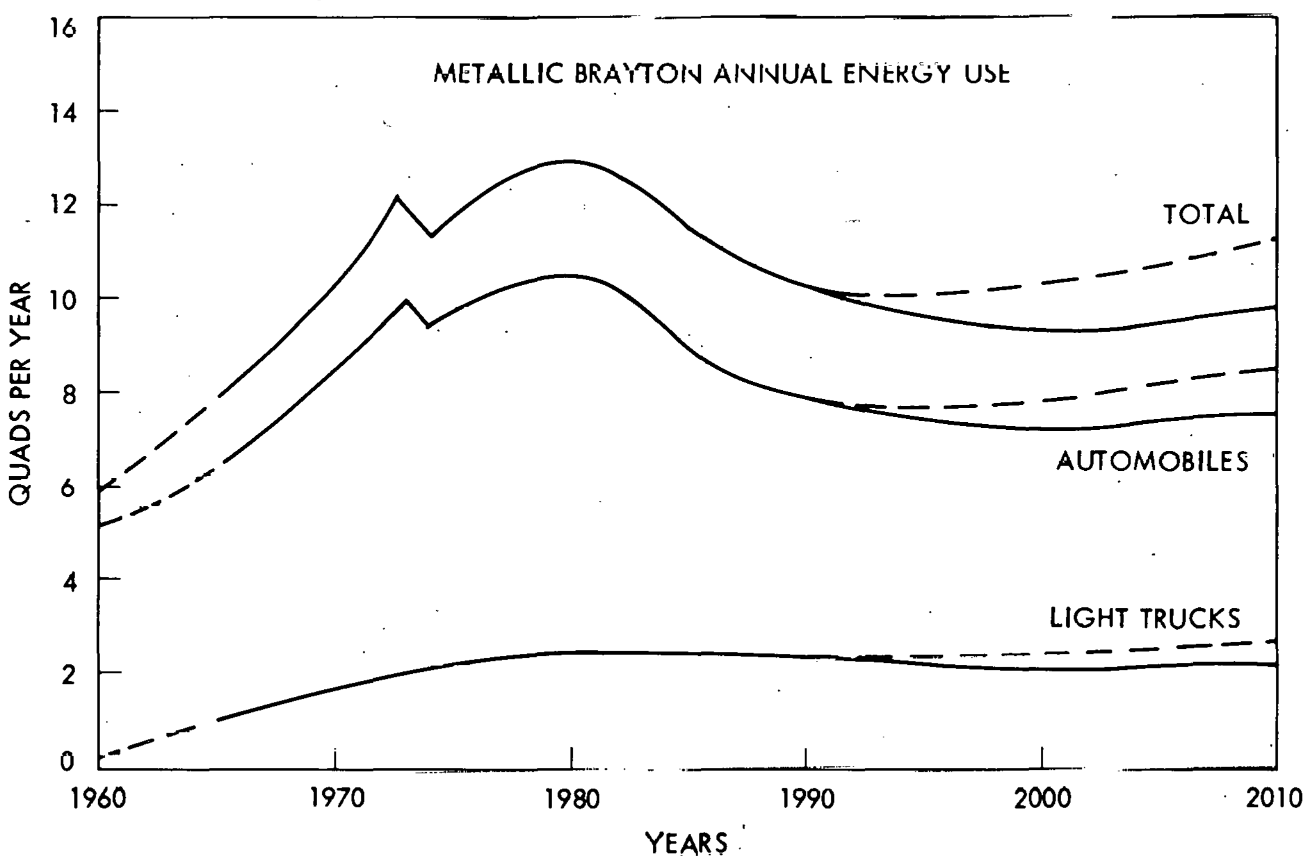

Figure 4.13. Fuel Consumption with Metallic Brayton Cycle Engines

4.5.3 CERAMIC BRAYTON

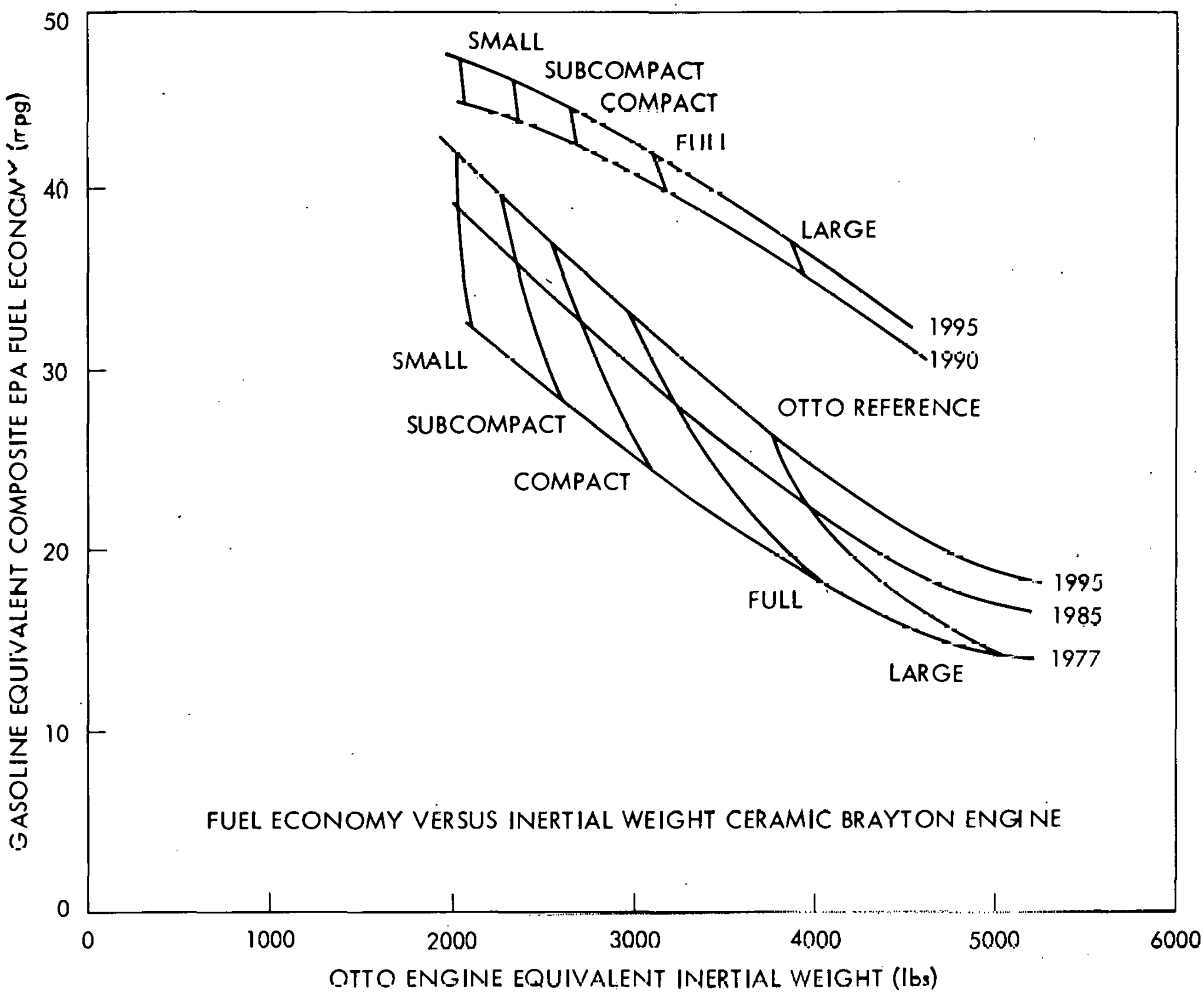

Figure 4.14. Fuel Efficiency vs. Inertial Weight of Ceramic Brayton Cycle Engines

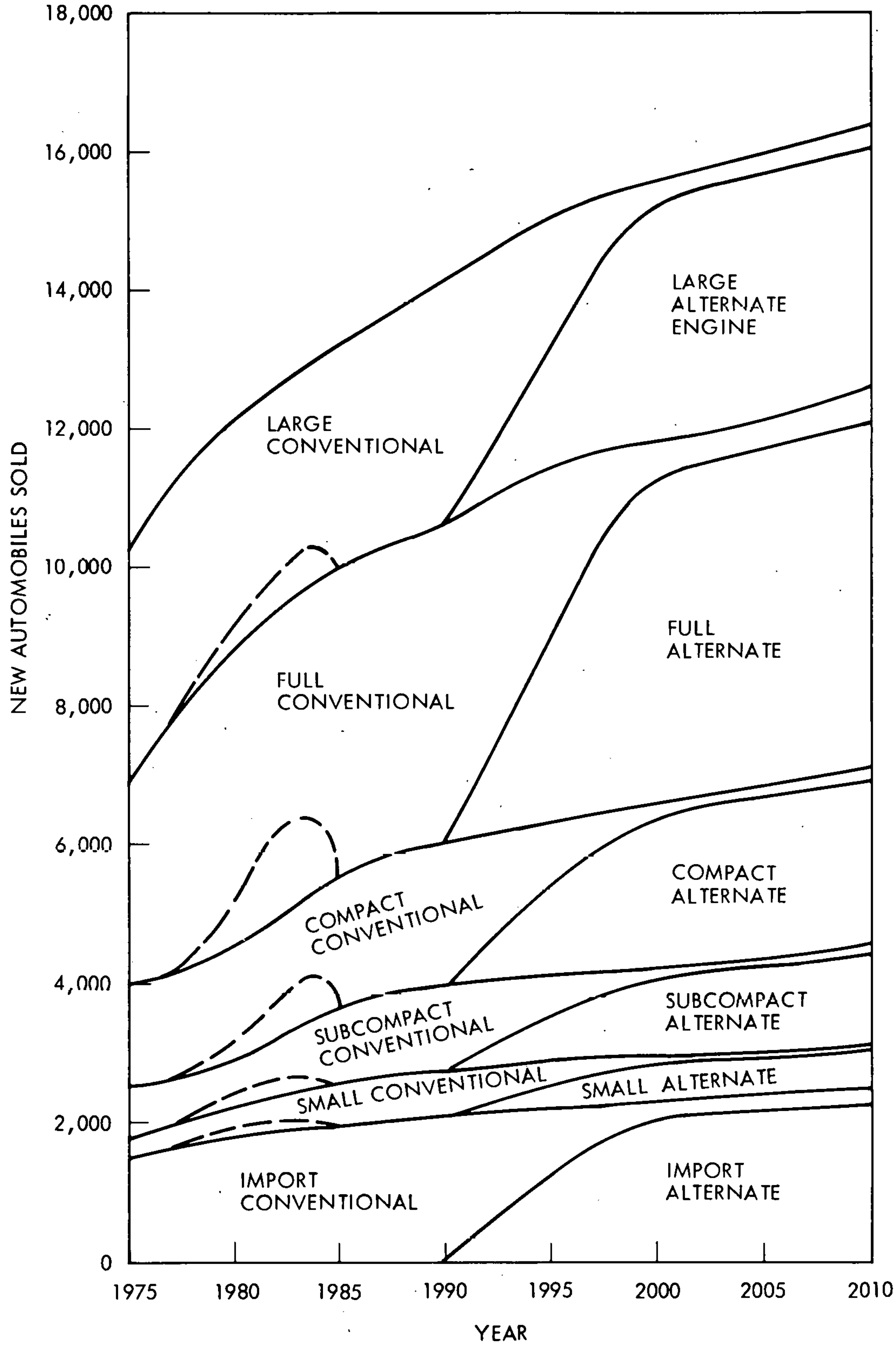

Figure 4.15. Future Fleet Size with Ceramic Brayton Cycle Engines

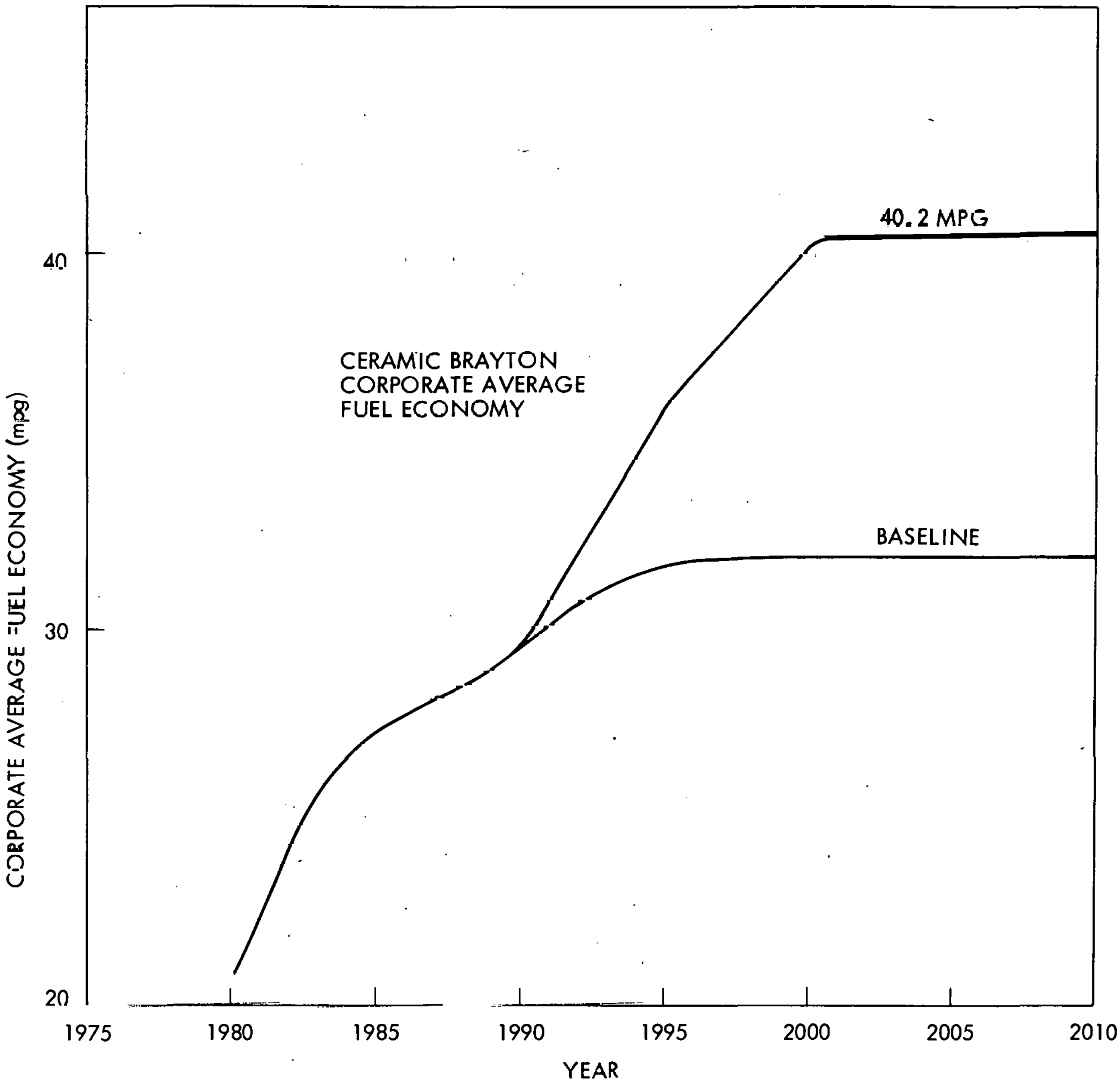

Figure 4.16. CAFE with Ceramic Brayton Cycle Engines

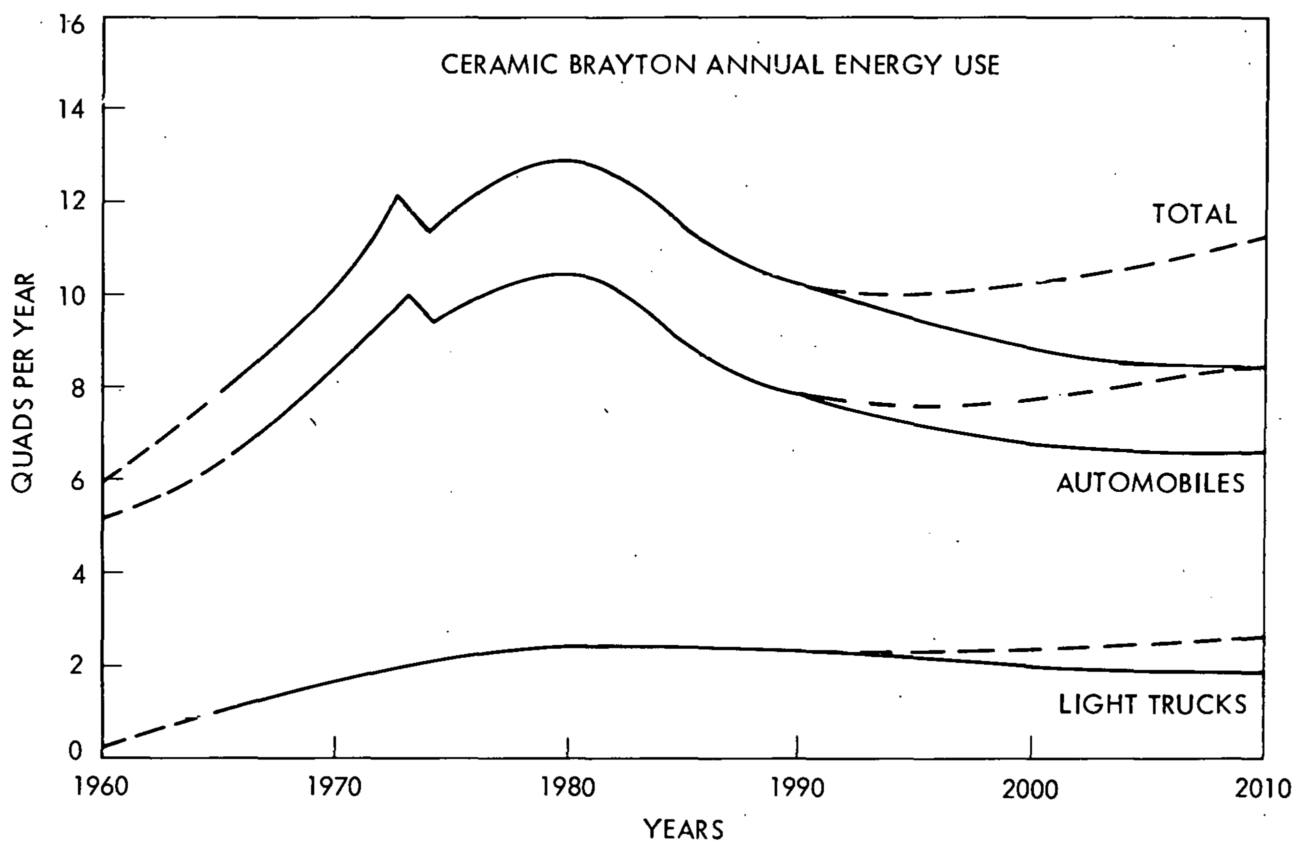

Figure 4.17. Fuel Consumption with Ceramic Brayton Cycle Engines

4.5.4 METALLIC STIRLING

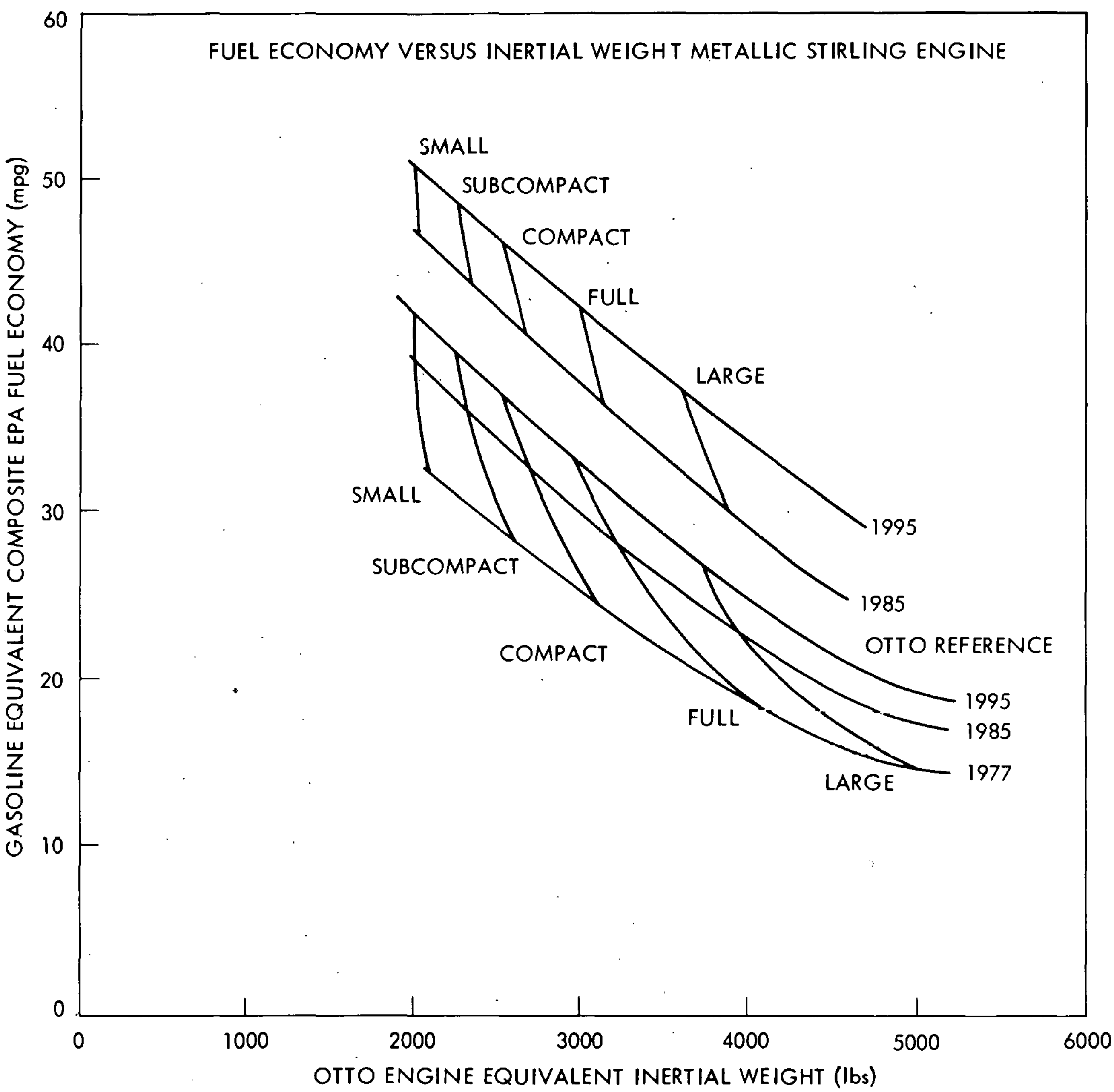

Figure 4.18. Fuel Efficiency vs. Inertial Weight of Metallic Stirling Cycle Engines

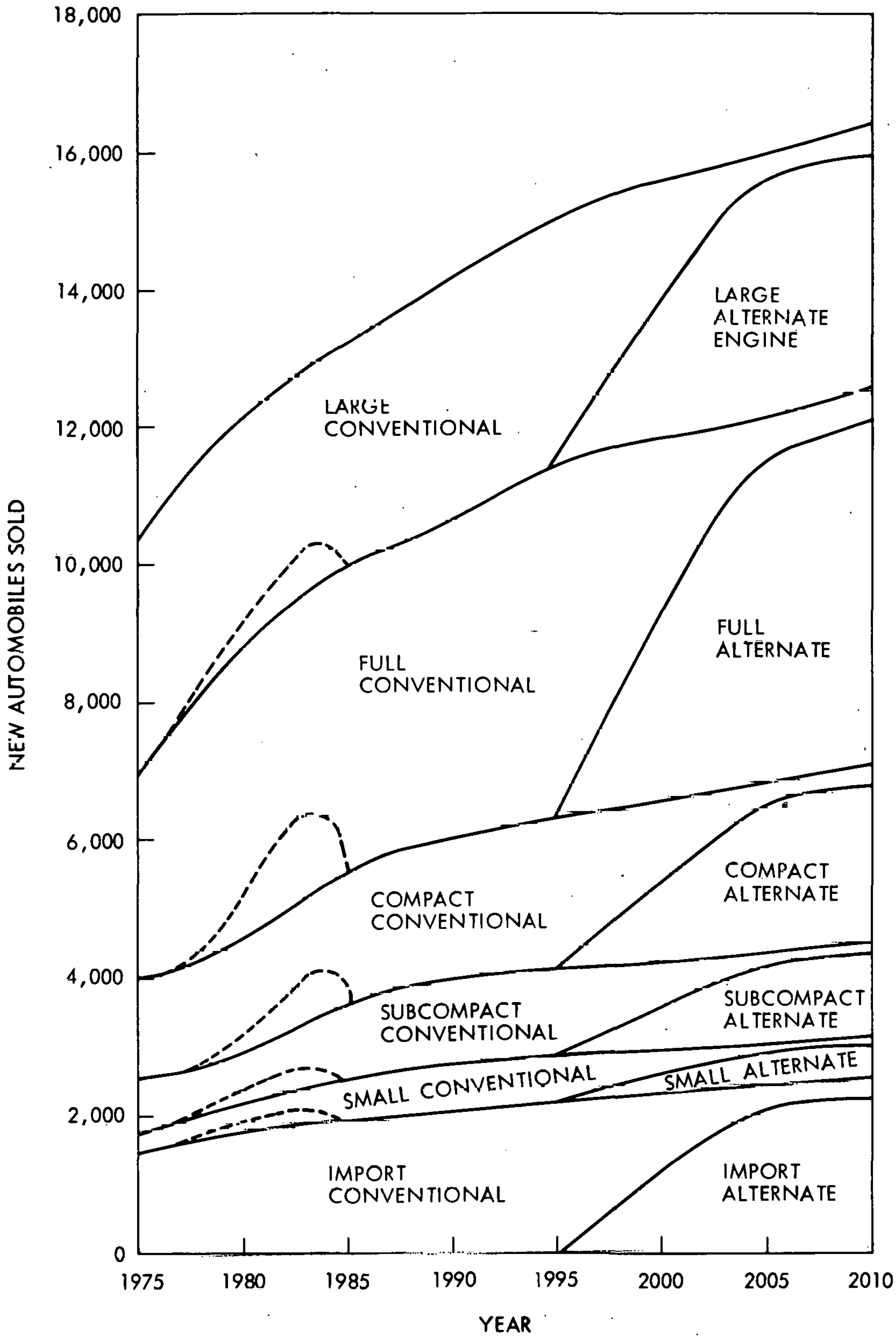

Figure 4.19. Future Fleet Size with Metallic Stirling Cycle Engines

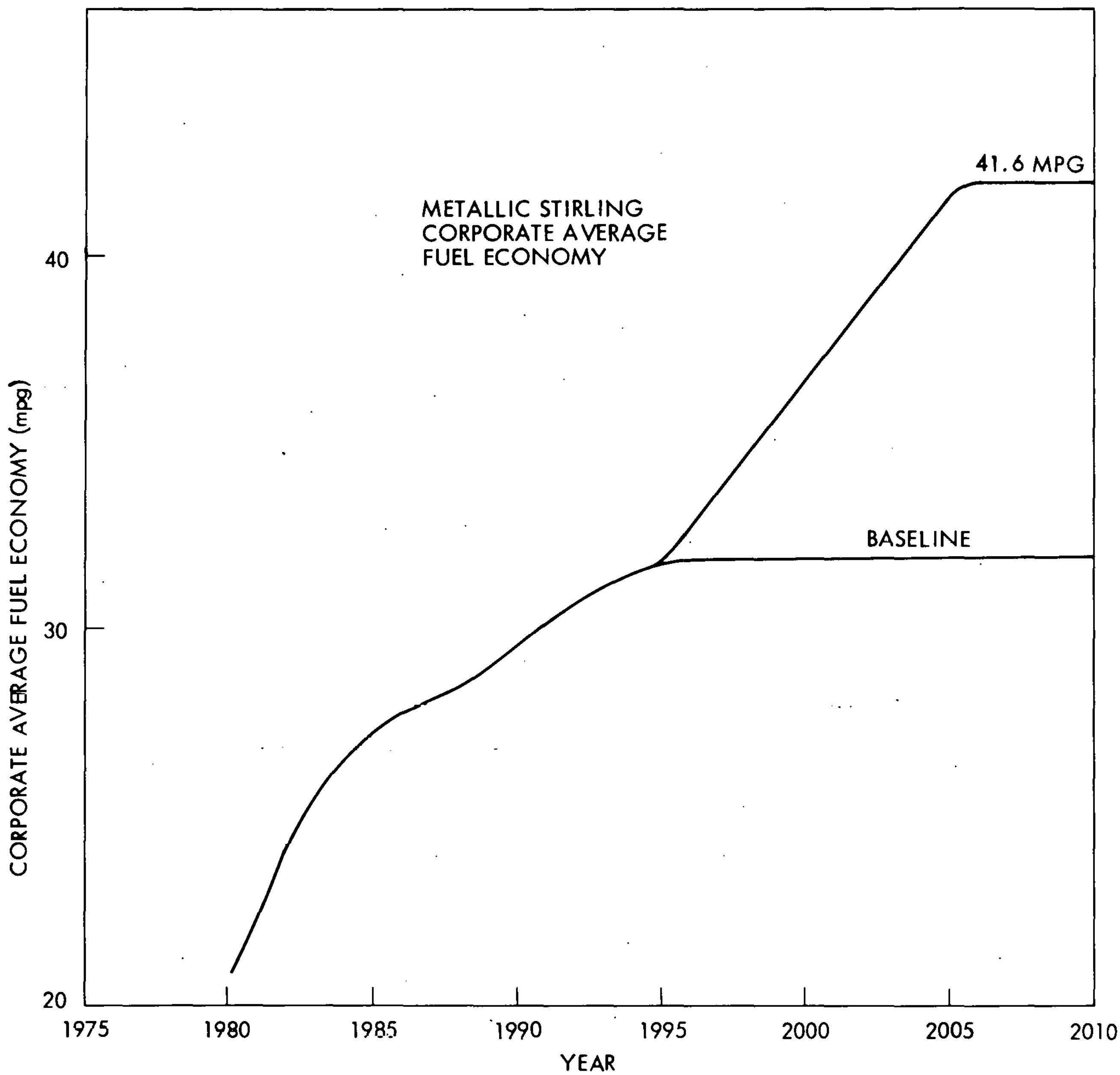

Figure 4.20. CAFE with Metallic Stirling Cycle Engines

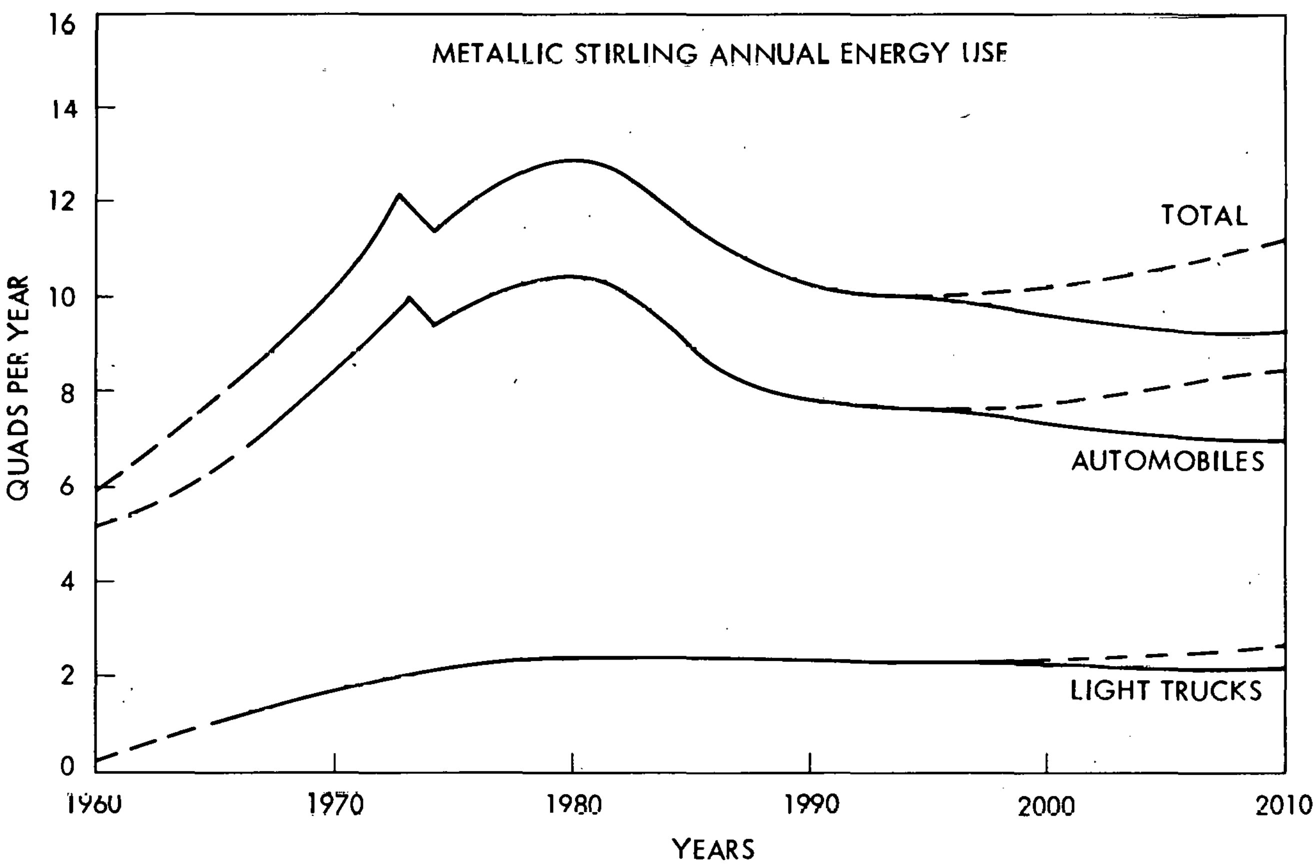

Figure 4.21. Fuel Consumption with Metallic Stirling Cycle Engines

4.5.5 CERAMIC STIRLING

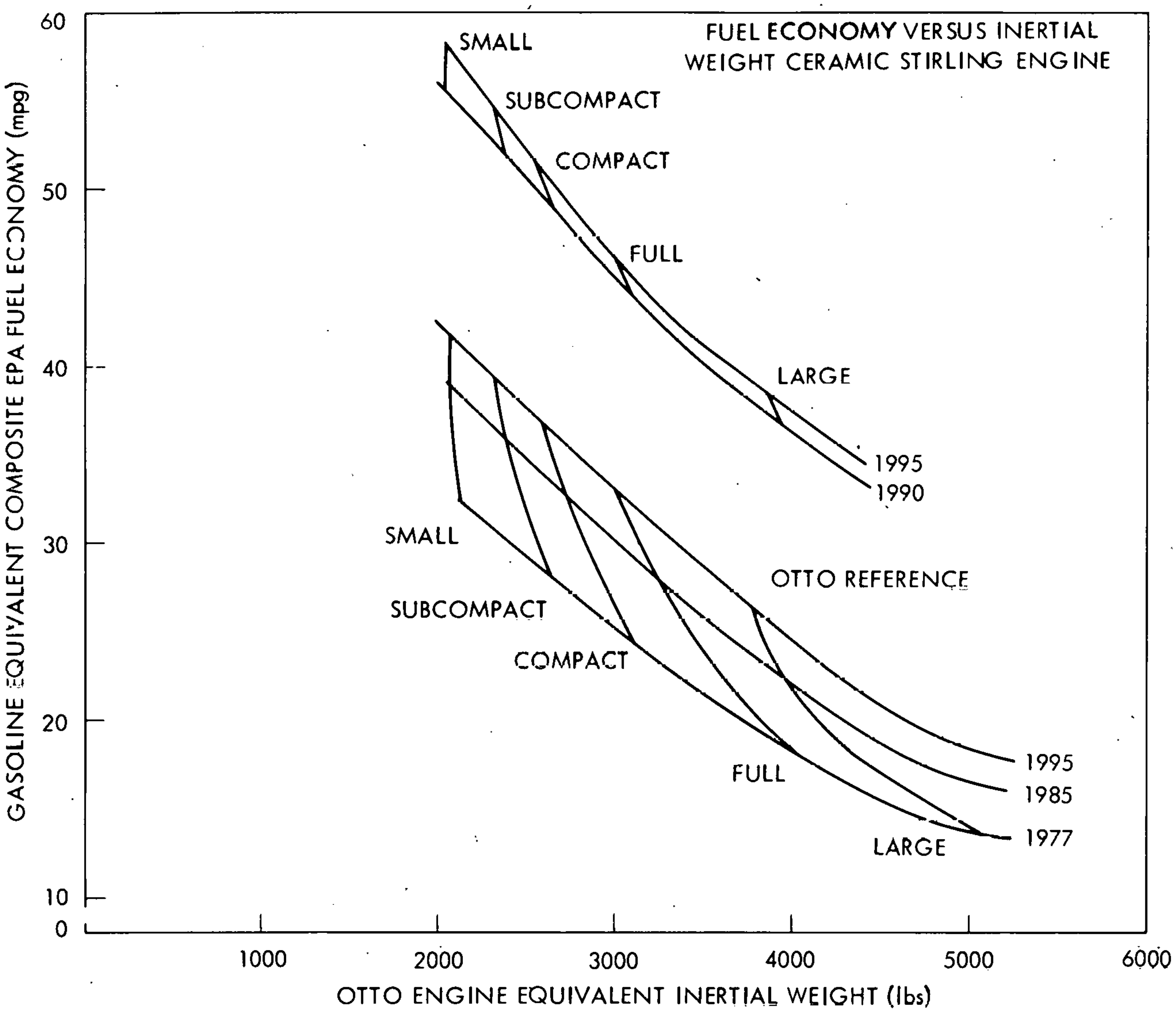

Figure 4.22. Fuel Efficiency vs. Inertial Weight of Ceramic Stirling Cycle Engines

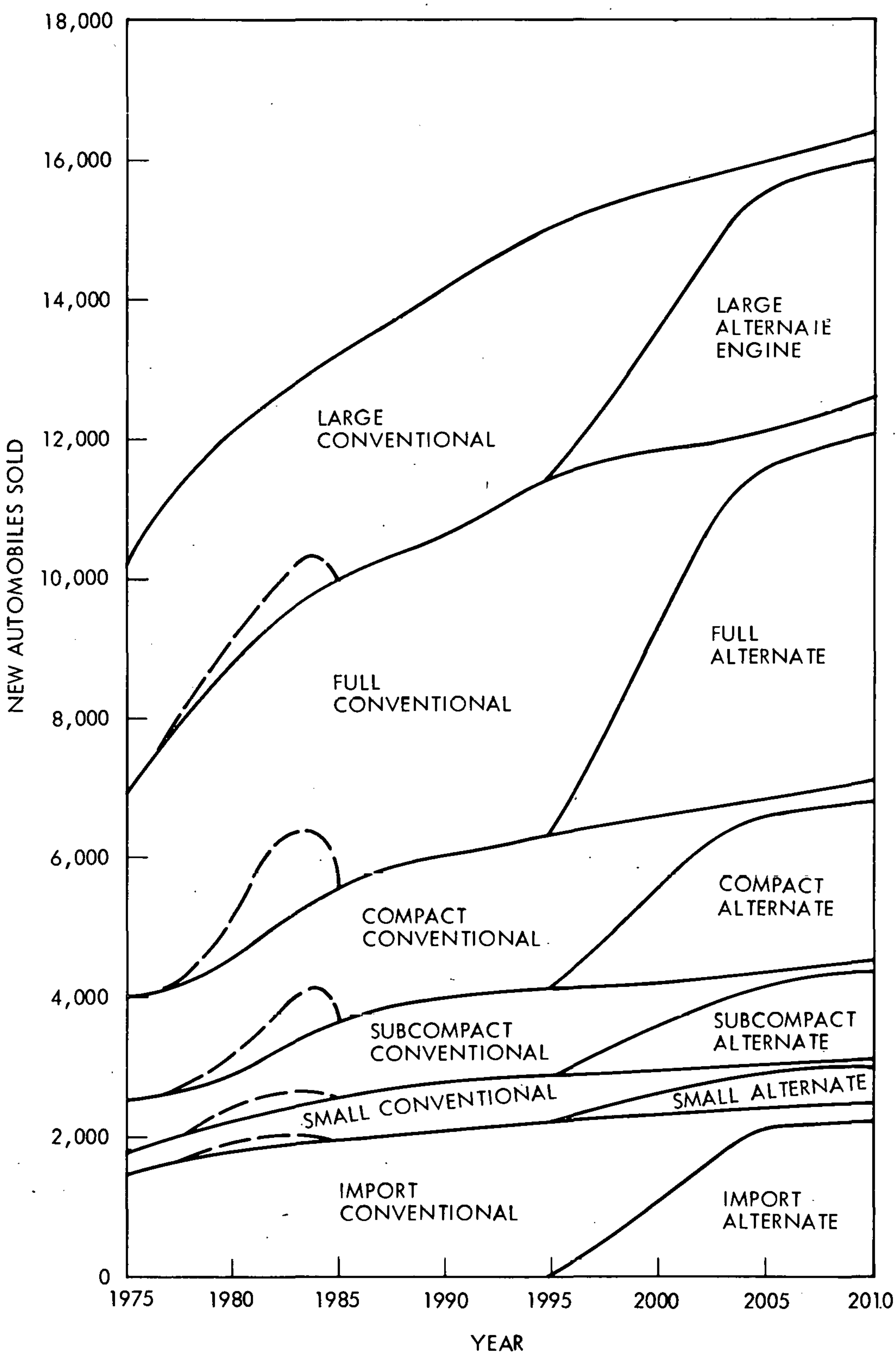

Figure 4.23. Future Fleet Size with Ceramic Stirling Cycle Engines

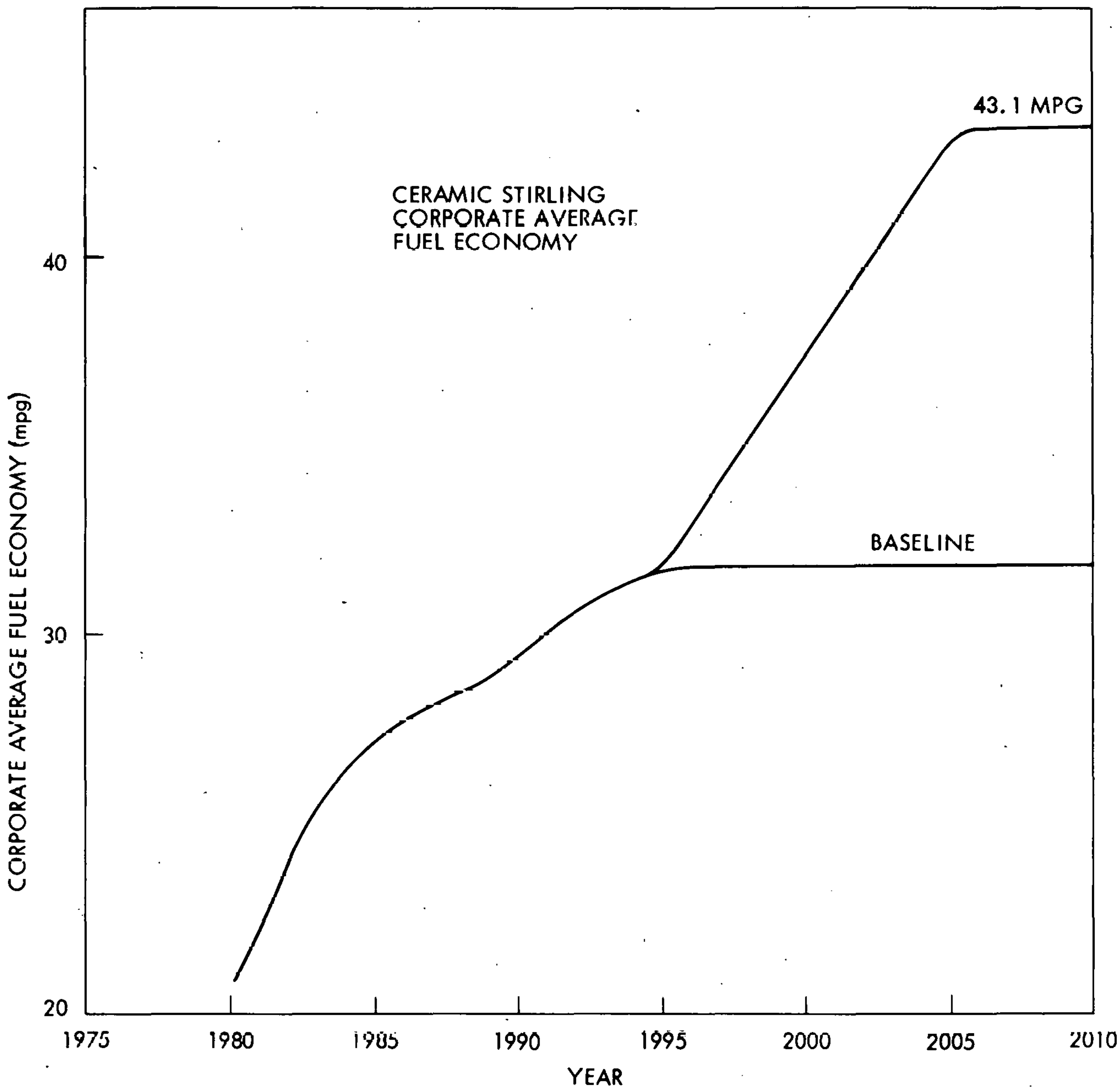

Figure 4.24. CAFE with Ceramic Stirling Cycle Engines

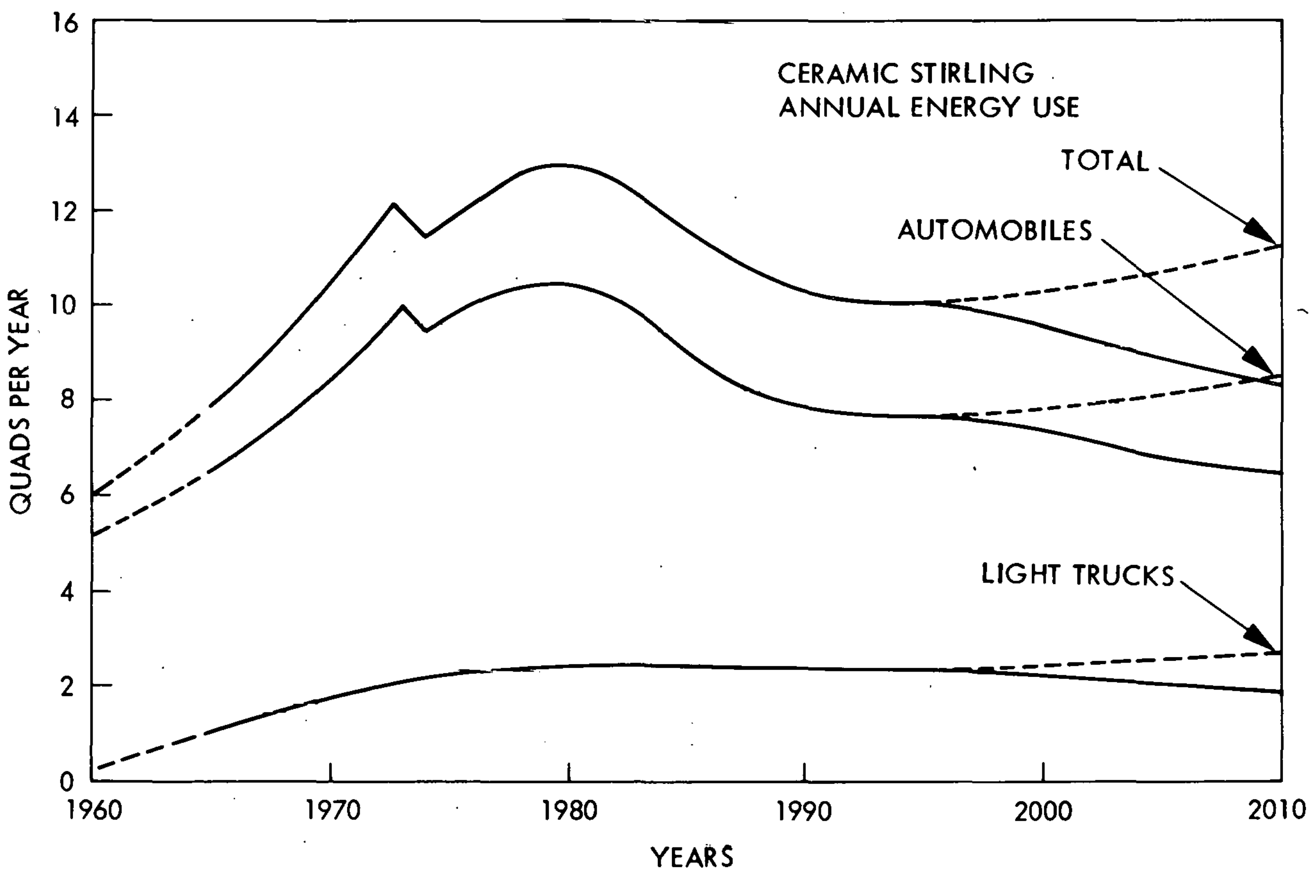

Figure 4.25. Fuel Consumption with Ceramic Stirling Cycle Engines

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