ECUT Energy Data Reference Series: High-Temperature Materials for Advanced Heat Engines

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G. J. Hane
D. R. Johnson**

July 1984

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ECUT ENERGY DATA REFERENCE SERIES:
HIGH-TEMPERATURE MATERIALS
FOR ADVANCED HEAT ENGINES

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D. R. Johnson

July 1984

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This series was a substantial undertaking that even now would not be accomplished were it not for the significant efforts of Dan Johnson. Dan saw the need for the series and had the vision to patiently persevere through all the obstacles in data gathering, report writing, and finally publication. In the later stages of this work, Judy Danko provided critical editorial assistance and encouragement. It was through her efforts that all the volumes of this series were completed and published simultaneously.

D. L. Brenchley
Project Manager

PREFACE

This study was completed for the Division of Energy Conversion and Utilization Technologies (ECUT) in the Department of Energy. The division's mission has three parts:

1. to monitor advances in basic scientific research and evaluate them for their applicability to energy conservation
2. to perform exploratory development on novel or innovative conservation concepts
3. to expand the technology base for advanced conservation technologies.

To aid in achieving this mission the ECUT staff established a planning and systems analysis function to identify and assess the array of opportunities for energy conservation R&D.

This on-going activity provides ECUT Staff with the information necessary to decide where to invest limited research dollars to derive the maximum benefit to the public. As part of its systems analysis role for ECUT, PNL published a general energy use data book covering all major end-use sectors (Imhoff, Liberman, and Ashton 1982). In contrast, the current ECUT Energy Data Reference Series is more narrowly targeted; each volume contains detailed capital stock and energy-use data for selected end-use sectors that are likely to be most impacted by existing or proposed ECUT R&D activities.

This volume relates to the ECUT R&D activity in high-temperature materials. The overall objective of this work element is to explore innovative concepts in high-temperature materials for applications in, among other things, advanced heat engines. The work specifically evaluates the potential of materials such as long-range ordered alloys and aluminides, and the development of technologies for joining ceramics used in advanced heat engines. In terms of impact and end-use market sectors, heat engines are only the intermediate application. This volume addresses the application of advanced heat engines in the transportation sector.

Other volumes in the ECUT Energy Data Reference Series include:

Hane, G. J. and D. R. Johnson. 1984. ECUT Energy Data Reference Series: Otto Cycle Engines in Transportation. PNL-5191, Pacific Northwest Laboratory, Richland, Washington.

Abarcar, R. B., G. J. Hane and D. R. Johnson. 1984. ECUT Energy Data Reference Series: Lightweight Materials for Ground Transportation. PNL-5192, Pacific Northwest Laboratory, Richland, Washington.

Young, J. K. and D. R. Johnson. 1984. ECUT Energy Data Reference Series: Ammonia Synthesis Energy-Use and Capital Stock Information. PNL-5194, Pacific Northwest Laboratory, Richland, Washington.

Chockie, A. D. and D. R. Johnson. 1984. ECUT Energy Data Reference Series: Boilers. PNL-5195, Pacific Northwest Laboratory, Richland, Washington.

The bulk of the research for this series was conducted in calendar year 1982. While the data portrayed in these publications have not changed dramatically, certain trends, particularly those that were forecast, may have shifted in the interim between research and publication.

The ECUT Data Reference Series is part of a series of studies in support of the ECUT research planning effort. Other ECUT publications are:

Bomelburg, H. J. 1983. Efficiency Evaluation of Oxygen Enrichment in Energy Conversion Processes. PNL-4917, Pacific Northwest Laboratory, Richland, Washington.

Chockie, A., et al. 1983. "An Overview of Research Requirements for Stationary Combustion Systems." In Proceedings of the 18th Intersociety Energy Conversion Engineering Conference, pp. 2092-2098. American Institute of Chemical Engineers, 345 E. 47 St., New York, New York.

Hane, G. 1983. Efficiency Evaluation of the DISC, DHC, and DI Diesel Engines. PNL-4568, Pacific Northwest Laboratory, Richland, Washington.

Hane, G., et al. 1983. A Preliminary Overview of Innovative Industrial Materials Processes. PNL-4505, Pacific Northwest Laboratory, Richland, Washington.

Hane, G., et al. 1984. A Review of Studies of Research Opportunities in Energy Conservation. PNL-4571, Pacific Northwest Laboratory, Richland, Washington.

Hopp, W., et al. 1981. An Overview of Energy Conservation Research Opportunities--Executive Summary. PNL-3944 Ex. Sum., Pacific Northwest Laboratory, Richland, Washington.

Hopp, W., et al. 1981. An Overview of Energy Conservation Research Opportunities. PNL-3944, Pacific Northwest Laboratory, Richland, Washington.

Hopp, W., et al. 1982. Identification of Energy Conservation Research Opportunities: A Review and Synthesis of the Literature. PNL-3966, Pacific Northwest Laboratory, Richland, Washington.

U.S. Department of Energy. 1981. The 1981 ECUT Work Element Appraisal. DOE/CE-0024, U.S. Department of Energy, Washington, D.C.

U.S. Department of Energy. 1983. Energy Conversion and Utilization Technologies Program Report, 1981-1982. U.S. Department of Energy, Washington, D.C.

Vallario, R. W. and D. E. DeBellis. 1984. State of Technology of Direct Contact Heat Exchanging. PNL-5008, Pacific Northwest Laboratory, Richland, Washington.

Vitullo, M., C. Winter and D. R. Johnson. 1984. The Executive Information System. PNL-5190, Pacific Northwest Laboratory, Richland, Washington.

BACKGROUND ON ECUT ENERGY DATA REFERENCE SERIES

The ECUT Energy Data Reference Series defines and assesses in quantitative terms the potential markets for expected ECUT R&D results. Each volume in the series provides data on a particular class of hardware systems that use and convert fuel. The data for each system include inventories of energy capital stocks, specific fuels consumption and product or service activity levels for the years 1980 and 2000, and average thermal efficiencies. Each data set characterizes the capital stock in a sector or subsector of the U.S. economy to which expected results from ECUT R&D projects can be applied. Each reference volume is consistent with the others in the series in format and approach, thus forming a framework for comparing certain aspects of ECUT R&D activities.

The ECUT Energy Data Reference Series serves as a benchmark for energy consumption and for conservation data for technologies addressed by the ECUT Program. The series incorporates the most accurate and up-to-date projections available in the open literature on energy capital stocks and their consumption levels. The series is specifically intended to be one of the many planning tools ECUT management can use to assess what potential impact its research projects will have. The series can also be used to demonstrate the potential impact of research on various stakeholders and constituencies, including industrial interest groups, budget decision makers, and the general public.

METHODOLOGY

The ECUT Energy Data Reference Series synthesizes data from the open literature, including technical reports, results of techno-economic models, industry surveys, and trade journal publications. A specific format was developed around the data items of interest and the intended purpose of the series. Each volume deals with a unique R&D application. Two scenarios are described--a baseline for 1980 and a projection for 2000.

The first line of effort is to extract the most recent data that are already in usable form in the open literature. In the case of competing data from disparate sources, the most reliable data are selected on the basis of the

completeness and extensiveness of the research. Where data sources appear to be equally reliable, an averaging method is employed to derive a single data point.

The second line of effort is to derive or extrapolate the needed data from the literature. For instance, if no energy consumption data are reported, production data can be multiplied by energy intensity data to derive consumption data.

Certain assumptions are used in projecting data points to the year 2000. The general rule is that the status quo is maintained throughout the projected future unless otherwise specified in the text. The energy capital stock is assumed to remain at its 1980 state of technology, and no competing technologies are considered to capture market share. This is in keeping with the objective of defining the potential impact of R&D results. In characterizing systems or processes with multiple fuel inputs, the mix of conventional fuels (those commonly used today) is allowed to change as each fuel is impacted by obvious and compelling factors, but no alternative, non-conventional fuels are projected as part of the fuel mix.

For simplicity, electricity is considered to be a fuel. This allows for a discussion of capital stocks that use electricity as an input without going through the machinations of breaking out power generation inputs, transmission losses, etc. These factors are considered to be constant at the national average, and are readily available in the literature.

SCOPE

The scope is defined along two directions: the data items of interest, and the end-use sector applications for ECUT R&D activities. The data items of interest, described below, are essential to a basic perspective on the potential impact of expected ECUT R&D results. Data items that change with time are defined for the year 1980 and projected for the year 2000.

DATA ITEMS

The data items considered in this series of reports are unit process hardware systems, efficiency estimates, capital stock information, fuel consumption demand, and product or service activity level.

Unit Process Hardware System

A unit process hardware system (UPHS) is generally defined as the least extensive configuration of components in a conversion or utilization system to which R&D results can be applied, and for which efficiency and fuel consumption estimates can be made. A UPHS is uniquely defined for each sector potentially impacted by ECUT R&D activity.

Efficiency Estimates

A specific definition of efficiency is developed for each application of each R&D activity. In general, the definition is based on the first law of thermodynamics, and is applied to the UPHS of interest. A broad discussion of major efficiency-loss mechanisms is included in each section on efficiency.

Capital Stock Information

Data derived for 1980 and projected for 2000 are based on the number of UPHSs in the economy that would be potential recipients of ECUT R&D results. UPHSs are disaggregated according to the type of fuel they use or convert. Other factors that help characterize the capital stock as a market for ECUT research are included as necessary and/or available.

Fuel Consumption Demand

Fuel consumption demand is developed for 1980 and projected for 2000. The thermal energy value (measured in Btu) of each fuel type consumed or converted by the capital stock of interest is developed for each application of each R&D activity. Electricity is considered to be a fuel. The extent to which use of alternative (non-conventional) fuels will penetrate the end-use sectors of interest by the year 2000 is not predicted. The relative contribution of conventional fuels in use today is, however, allowed to change with the turnover of capital stocks and with trends in consumer preferences. No attempt is made to project the availability of conventional fuels in 2000.

Product or Service Activity Level

Data on the demand for each product or service resulting from the use or conversion of energy by the capital stock of UPHSs are developed for 1980 and projected for 2000.

SUMMARY

This report summarizes information that describes the use of high-temperature materials in advanced heat engines for ground transportation applications. Applications discussed in this report are:

- automobiles
- light trucks
- medium and heavy trucks.

The information provided on each of these modes includes descriptions of the average conversion efficiency of the engine, the capital stock, the amount of energy used, and the activity level as measured in ton-miles. This information is summarized in Tables S.1 and S.2.

TABLE S.1. Research and Development Applications Summary

Data Item/Fuel Type	UPHS Average Efficiency	# Unit Process Hardware Systems		Fuel Consumption Demand (Btu)		Product or Service Activity Level (ton-miles)	
	1980	1980	2000	1980	2000	1980	2000
<u>AUTOMOBILES</u>							
Gasoline	26%	104,564,000	110,000,000	$9,740 \times 10^{12}$	$7,050 \times 10^{12}$	$2,060 \times 10^9$	$1,910 \times 10^9$
<u>LIGHT TRUCKS</u>							
Gasoline	26%	28,900,000	33,300,000	$2,717 \times 10^{12}$	2.82×10^{12}	877,000,000	1,063,000,000
LPG	26%	87,000	108,000	7.25×10^{12}	7.55×10^{12}	2,600,000	3,620,000
<u>MEDIUM AND HEAVY TRUCKS</u>							
Gasoline	26%	3,575,000	3,293,000	651×10^{12}	600×10^{12}	221×10^9	169×10^9
LPG	26%	10,760	9,930	4.0×10^{12}	4.4×10^{12}	555×10^6	425×10^6

TABLE S.2. Market Data Summary

Data Item/Fuel Type	Total # Unit Process Hardware Systems 1980	Total Projected # Unit Process Hardware Systems 2000	# UPHS Due to Industry Capacity Expan- sion (Increased Service Demand) 2000	# UPHS Due to Replacement of Obsolete Units 2000	# UPHS from 1980 Remaining in Service 2000
<u>AUTOMOBILES</u>					
Gasoline	104,564,000	110,000,000	5,436,000	101,427,000	3,136,920
<u>LIGHT TRUCKS</u>					
Gasoline	28,900,000	33,300,000	4,400,000	28,370,000	532,000
LPG	87,000	108,000	21,000	85,400	1,650
<u>MEDIUM AND HEAVY TRUCKS</u>					
Gasoline	3,575,000	3,293,000	--	2,399,000	894,000
LPG	10,760	9,930	--	7,240	2,690

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1.0 HIGH-TEMPERATURE MATERIALS FOR ADVANCED HEAT ENGINES

A number of alternative concepts for automotive propulsion are being considered to replace the Otto cycle engine. These alternative propulsion systems include the following:

- Stirling engine
- automotive gas turbine
- adiabatic diesel engine.

These concepts are currently being researched and developed to be equal or superior to the presently used Otto cycle engines in terms of performance, fuel economy and cost. In addition, the advanced heat engines are expected to have low exhaust emissions, to have low levels of noise and vibration, and to use alternative fuels.

These advanced heat engines must operate at temperatures and pressures higher than conventional automotive engines. This combination (high pressure, high temperature and highly erosive/corrosive engine environments) presents severe materials property requirements that may not even be met by currently available technology. Examples of expected operating conditions are:

- for the Stirling engines, temperatures of 820°C (1508°F) or higher at the heater head and maximum hydrogen pressure of 20 MPa (2899 psi)
- for the automotive gas turbine, turbine inlet temperatures expected to be greater than 1150°C (2100°F), possibly as much as 1260°C (2300°F)
- for the adiabatic diesel engine, peak combustion temperature of 1200°C (2200°F) and a peak combustion pressure of 13.8 MPa (2000 psi) occurring over high frequency stress cycles.

The candidate advanced materials that can operate under the severe conditions expected of the advanced heat engines include:

- structural ceramics
- long-range ordered alloys
- intermetallic compounds (e.g., aluminides)
- superalloys.

The temperature limits for these advanced materials are roughly as follows:

- ceramics - greater than 1100°C
- long-range ordered alloys and intermetallics - up to 1100°C
- superalloys - up to 900°C.

Specific applications of advanced materials are discussed in the following sections:

1.1 STIRLING ENGINES

The heater tubes, cylinder heads, regenerator housings, and piston domes are the hot-end components of the Stirling engine that are critical. Table 1.1 lists the materials currently used for the components in the prototype and the alternative materials selected for investigation. The composition for heat tube materials (wrought alloys) and for cylinder head and regenerator housing materials (cast alloys) is given in Tables 1.2 and 1.3, respectively. Specific areas for R&D in materials include hydrogen permeation, environmental effects on mechanical properties and development of advanced processing techniques that lead to reduced manufacturing cost.

1.2 ADIABATIC DIESEL ENGINE

The materials used for the hot components of the adiabatic diesel engine (ADE) must be able to retain strength over a long period of time while operating at the high pressures and temperatures occurring over high frequency stress cycles. The current design of the ADE considers the use of both ceramic and metallic materials for the hot section components.

Some of the ceramic materials under evaluation for the critical components are listed in Table 1.4. An experimental piston design using a ceramic piston cap with an aluminum metal base is shown in Figure 1.1.

There are difficulties associated with design and manufacture using structural ceramics; these include degradation due to environmental attack and due to local stress concentrations at superficial point contracts. Also, engine design is frequently complicated by a need to use thermal barriers to reduce heat losses.

TABLE 1.1. Alloys Presently Used and Alternatives Under Evaluation for the Automotive Stirling Engine (Liu 1981)

<u>Component</u>	<u>Materials Currently Used in the P-40</u>	<u>Alternative Materials Under Evaluation</u>
1. Heater Tubes	N-155	XN-520 (Climax Molybdenum) Inconel 625, 718 Inconel X-750 Incoloy 901, 800H Sandvik 12 RN 72 Sanicro 32X Sanicro 31H Avesta 253 MA 19-9DL HS-188 A-286 Nitronic 40
2. Cylinder Heads and Regenerator Housings	HS-31	XF-818 (Climax Molybdenum) CRM-60 SAF-11
3. Piston Domes	N-155, Nimonic 80A machined from bar	Inconel 718, deep drawn or hydraulically formed sheet

An alternative approach to the use of structural ceramics is to use metallic materials coated with thermal barriers. The components being evaluated are:

- pistons where base metal is coated with yttrium-stabilized zirconia
- cast alloy cylinder head and lining coated with insulating materials such as zirconia and chromium oxides
- stainless steel exhaust manifold coated with zirconia.

1.3 ADVANCED GAS TURBINES

Advanced gas turbines (AGT) must operate at temperatures distinctly higher than conventional piston engines if they are to achieve the desired performance goals. Unfortunately, state-of-the-art materials, both ceramic and metallic, do not have adequate anisotropic or directional strength and corrosion resistance to perform under the required severe operating conditions. Improved ceramic parts are the probable material of choice in the internal hot sections

TABLE 1.2. Heater Tube Alloys Under Evaluation for the Automotive Stirling Engine
(Liu 1981)

Alloy	C	Mn	Si	Cr	Ni	Co	Mo	W	Ta+Nb	Al	Y	B	Zr	Ti	Fe	Other
XN-520	0.05	0.5	0.1	20.0	Bal		5.0	5.0	2.0	1.0	0.05	0.005	0.05	0.2		
Inconel 625	0.05	0.5	0.25	21.0	Bal		9.0		3.7	0.2				0.2	2.5	
Inconel 718	0.04	0.2	0.2	18.5	Bal		3.0		5.1	0.5				0.9	18.5	
Inconel X-750	0.04	0.5	0.25	16.0	Bal				1.0	0.65				2.5	7.0	
Incoloy 901	0.05	0.5	0.3	12.5	42.0		6.0			0.2		0.015		2.7	Bal	
Incoloy 800H	0.01	0.7	0.5	22.5	32.6					0.54				0.52	Bal	
12 RN 72	0.10	1.8	0.4	19.0	25.0		1.4					0.006		0.5		
Sanicro 32X	0.09	0.6	0.6	21.0	31.0			3.0		0.4				0.4	Bal	
Sanicro 31H	0.07	0.6	0.6	21.0	31.0					0.3				0.3	Bal	
Nitronic 400	0.03	9.4	0.49	20.8	7.0										Bal	0.34 N
253 MA	0.08	0.08		21.0	11.0											0.17 N
A-286	0.06	1.01	0.6	14.4	24.7		1.2							2.1		0.3 Cu, 0.26 V
19-9 DL	0.30	1.00	0.50	19.0	9.0		1.4	1.3	0.4					0.30	Bal	
N-155	0.12	1.5	0.50	21.0	20.0	19.0	3.0	2.5	1.0						Bal	
HS-188	0.10	1.25	0.3	22.0	22.0	Bal		14.0							3.0	0.04 La

TABLE 1.3. Cylinder Head and Regenerator Housing Materials Under Evaluation for the Automotive Stirling Engine (Liu 1981)

Alloy	C	Mn	Si	Cr	Ni	Co	Mo	W	Ta+Nb	Al	Y	B	Zr	Fe	Other
HS-31 (X-40)	0.5	0.5	0.5	25.0	10.0	54.0		7.5			0.5		0.9		
XF-818	0.21	0.12	0.28	18.0	17.9		7.6		0.4			0.75	0.003	Bal	0.115 N
CRM-60	1.05	5.0	0.5	22.0	5.0		1.0	1.0	1.0			0.003		Bal	
SAF-11	Composition not known														

TABLE 1.4. Materials Under Evaluation for Ceramic-Type Adiabatic Diesel Engine Hot Components (Liu 1981)

Component	Materials Under Evaluation
Piston cap	Hot-pressed silicon nitride (HPSN) Sintered silicon nitride (SSN) Reaction-bonded silicon nitride (RBSN) Sintered silicon carbide (SSC) Partially stabilized zirconia (PSZ)
Bolt fastener	Waspaloy Udimet 700 R-41
Cylinder head hot plate	Hot-pressed silicon nitride (HPSN) Sintered silicon nitride (SSN) Zirconia
Deck spacer ring	Hot-pressed silicon nitride (HPSN) Sintered silicon nitride (SSN) Zirconia
Cylinder liner	Hot-pressed silicon nitride (HPSN) Sintered silicon nitride Partially stabilized zirconia (PSZ)
Exhaust manifold	ZrO ₂ -coated stainless steels

of the AGT because of their potential for high temperature capability. Ceramics are preferred because their constituents are lightweight, readily available and inexpensive as compared to imported strategic elements contained in current superalloys.

Although ceramic parts have been strengthened significantly, failures of static ceramic components still frequently occurred during rig and engine tests. These failures appear to be induced by contact stresses or transient

FIGURE 1.1. Experimental Piston Design for a Ceramic-Type Adiabatic Diesel Engine (Bryzik 1978)

thermal stresses during start-up. Use of structural ceramics for turbine blades has been more successful because of the more uniform temperatures to which turbine blades are exposed. Controlling fabrication procedures and identifying flaws are two major technical barriers that can be addressed by materials research.

Figure 1.2 shows the ceramic components being considered for the GM AGT-100 engine. Metallic materials with ceramic thermal barriers such as yttria-stabilized zirconia are frequently used for static components such as plenum assemblies and vanes. Use of lamalloy and transpiration cooling are other means available to improve the performance of AGT components.

With a significant amount of adaptation, materials technology presently available may allow the advanced heat engines to capture a little of the potential for increased efficiency offered by operation at increased temperature and

FIGURE 1.2. AGT-100 Ceramic Parts Under Development (DOE 1980)

pressure. However, it is only through the successful development of the desirable properties and the feasibility for mass production of the materials that the greatest potential for engine efficiency improvements will be realized.

The principal difficulty in assessing the energy impact of alternative automotive engines is the fact that projections of the future characteristics of the transportation system are based on historical data and trends. This is complicated by the lack of data on the performance of the alternative engine concepts. The references used to develop the data were prepared during the period 1974-1979 when there was a strong consensus that alternative automotive engines were needed. Data from reports earlier than 1974 were considered dated because they were based on historical trends (1974 and prior years) that do not reflect more current trends (1976 to the present). The automobile has since undergone radical changes in terms of both the configuration (size and power availability) and sales.

2.0 HIGH-TEMPERATURE MATERIALS FOR ADVANCED HEAT ENGINES IN AUTOMOBILES

The advanced engine concepts being researched and developed are anticipated to compete with currently used Otto and diesel cycle engines for automotive propulsion. The impact of R&D in advanced engine concepts can be assessed from its anticipated share of the future capital stock and the concomitant improvement in energy use in transportation.

On the other hand, research in high-temperature materials does not affect energy use in the transportation sector directly, but has indirect effect through the use of advanced engine concepts as alternative automotive propulsion systems. Research and development can overcome materials limitations that impede the development of advanced engine concepts and these concepts can subsequently be established as viable alternatives to the Otto and diesel cycle engines.

The analysis of the impact of research in high-temperature materials in transportation should then be conducted by consideration of the following:

- technical impact
- market impact.

The technical impact addresses the technical barriers to full implementation of advanced heat engines. Research on high-temperature materials seeks to overcome the limitations of operation at high pressures and temperatures that are characteristic of currently available materials. The technical impact of high-temperature materials research is discussed in the sections that follow.

The market impact can be assessed by assuming that all technical barriers to the use of advanced engine concepts in transportation are overcome and they are able to capture their potential share of the market and the future capital stock. Advanced engine concepts will compete in the same market defined for Otto and diesel cycle engines in transportation.

2.1 EFFICIENCY ESTIMATES

The various ways by which the efficiency of energy conversion in automotive transportation systems can be estimated is shown in Figure 2.1. For a

FIGURE 2.1. Energy Use in Passenger Car During EPA Cycle (Hopp 1981)

passenger car using a state-of-the-art Otto cycle engine, the thermal efficiencies during an EPA specified driving cycle are as follows:

- The indicated thermal efficiency is 38%. This represents the conversion of input energy into work done against the piston through the expansion of the combustion gases. The theoretical thermal efficiency is close to this value.
- The brake thermal efficiency is 25%. This represents the conversion of the input energy into work delivered by the power shaft of the engine.

The brake specific fuel consumption (bsfc) is a commonly used basis for comparing alternative propulsion systems. The bsfc provides a measure of the amount of fuel used (lb/hr) to deliver one brake horsepower (bhp) at the output shaft. It can be noted that the brake thermal efficiency is inversely related to the bsfc (i.e., lower bsfc results in higher brake thermal efficiencies) and can be calculated from the bsfc upon inclusion of the heating value of the fuel. Figure 2.2 shows expected improvements in specific fuel consumption of the AGT 101. The turbine inlet temperature tolerance is raised by incorporation of additional and improved ceramic turbine parts at the various stages of development of the advanced gas turbine. Increase in the turbine inlet temperature allows for an improvement in the bsfc as well as in the net power output of the turbine. In Figure 2.3 the bsfc of various engine types is compared.

When the engine is used in a complete transportation system, such as an automobile, added factors such as weight and speed are introduced. In this case, passenger car fuel economy in miles per gallon of fuel consumed (mpg) makes a more appropriate measure for comparison; it is also a measure more readily understood by car buyers. The automotive fuel economy standards for the years 1967 to 1980 and the EPA projected fuel economy standards to 1985 are shown in Figure 2.4. The new car fuel economy for 1980 (calculated using manufacturers' sales projections) is 22.4 mpg compared to on-road new car fuel economy based on actual sales data of 20.4 mpg. It can be noted that estimates of new car fuel economy based on sales projections markedly exceed the EPA fuel economy standards for 1980. On-road new car fuel economy, however, has just

FIGURE 2.2. Projected Specific Fuel Consumption of the AGT 101 at Various Stages of Development (Garrett/Ford 1981)

barely surpassed the fuel economy standard of 20.0 mpg for 1980. The fuel economy expected of advanced heat engines used in automobiles will have to be compared to the out-year mpg values in Figure 2.4.

In Figure 2.5 the projected fuel economy of the Garrett/Ford advanced gas turbine (AGT 101) is compared to the fuel economy of diesel- and gasoline-powered vehicles for various vehicle inertia weights. The potential improvement over the current AGT vehicle is also shown.

2.1.1 Loss Mechanisms

An estimate of the energy distribution in a typical passenger car powered by an Otto cycle engine has been shown in Figure 2.1. As indicated in Figure 2.1, there are four levels at which improvements in energy conversion can be made. Replacement of currently used engines with advanced heat engines will

FIGURE 2.3. Comparison of Brake Specific Fuel Consumption of Various Engines (Glance 1979)

achieve improvements at Level 1 and 2. A new engine concept (Stirling thermodynamic cycle versus Otto thermodynamic cycle) will introduce improvements at Level 1, while actual hardware developed (prototype or mass-produced engines) will effect changes at Level 2.

A comparison of the energy distribution between a basic turbocharged diesel engine and an adiabatic diesel engine (ADE) with turbocompounding is shown in Figure 2.6. The ADE exhibits an improvement of fuel economy from the 0.36 lb/bhp-hr of the basic diesel engine to 0.285 lb/bhp-hr, and increases power by more than 30% for the same fuel input.

*Based on manufacturers' sales projection

^aJ.D. Murrell, J.A. Foster, and D.M. Bristol, Environmental Protection Agency, Passenger Car and Light Truck Fuel Economy Trends through 1980, SAE Paper 800853.

^bCalculated using EPA fuel economy values. It should be noted that EPA new car fuel economy values for 1979 and 1980 are calculated using manufacturers' sales projections, while the on-road new car fuel economy is based on actual sales data. The source for the on-road fuel economy is: Energy and Environmental Analysis, Inc., The Highway Fuel Consumption Model - Fourth Quarterly Report, prepared for the U.S. Department of Energy, Washington, D.C., July 1981.

^cU.S. Department of Transportation, Federal Highway Administration, Highway Statistics, Washington, D.C., annual.

FIGURE 2.4. Automotive Fuel Economy Standards, 1967 to 1985 (Oak Ridge 1981)

FIGURE 2.5. Projected Vehicle Fuel Economy of the AGT 101 Compared to the Diesel- and Gasoline-Powered Vehicles (Garrett/Ford 1981)

2.2 CAPITAL STOCK INFORMATION

2.2.1 Capital Stock Information, 1980

Oak Ridge (1981) estimates that there were 104,564,000 automobiles in use in 1980. The breakdown of automobiles among the six categories of vehicles is shown in Table 2.1.

Information describing the sales of domestic and imported automobiles in 1980 is shown in Table 2.2. The table shows that subcompact cars had the largest share of the market at 38.0%, with midsize following at 33.7%, and large cars third at 13.4%. This is a notable market shift from 1978 when midsize had the largest share of the market at 31.6%, followed by large and subcompact

FIGURE 2.6. Comparison of the Energy Balance Between Basic and Adiabatic Diesel Engines (Bryzik 1980)

TABLE 2.1. Automobile Stock in 1980 by Size Category

Category	Number	Percent of Total
Two seater	1,687,000	1.6%
Minicompact	7,010,000	6.7%
Subcompact	20,042,000	19.2%
Compact	15,772,000	15.1%
Midsized	25,471,000	24.4%
Large	34,582,000	33.1%

cars, which had 20.% and 19.9% of the market, respectively. A comparison of the market shift between 1978 and 1980 is provided in Table 2.3.

Information on the survival and scrappage rates of automobiles is illustrated in Figure 2.7 and Table 2.4. The survival probability curve for automobiles as a function of their age is shown in Figure 2.7. One can see from the figure that the "half-life" for automobiles is approximately 10 years. Points on the curve are tabulated in Table 2.4, which also presents information on scrappage rates, the number of vehicles in operation, and the percent of vehicle miles traveled (by age group).

TABLE 2.2. Motor Vehicles in Use, Sales, and New Registration in the United States, 1980
(Oak Ridge 1981)

	Motor Vehicles in Use as of July 1, 1980 (in thousands)	Sales					
		Domestic		Imported ^(a)		Total	
		(in thousands)	Percentage Domestic	(in thousands)	Percentage Import	(in thousands)	Percentage by Class
Automobiles	104,564	6,369 ^(b)	100.0	2,527	100.0	8,896	100.0
Two seater	1,687	37	0.6	179	7.1	216	2.4
Minicompact	7,010	169	2.6	234	9.3	403	4.5
Subcompact	20,042	1,444	22.7	1,936	76.6	3,380	38.0
Compact	15,772	533	8.4	175	6.9	708	8.0
Midsize	25,471	2,993	47.0	3	0.1	2,996	33.7
Large	34,582	1,193	18.7	0	0.0	1,193	13.4
Fleet (4+)	10,433 ^(c)						
Personal	94,131						
Motorcycles	7,400	130	10.4	1,120	89.6	1,250	100.0
Mopeds	1,000	(d)		(d)		210	100.0
Recreational vehicles	6,000	308 ^(e)	100.0	0	0.0	308	100.0
Trucks ^(f)	35,268	2,035	100.0	485	100.0	2,520	100.0
Light	30,119	1,765	86.7	480	99.0	2,245	89.1
Medium	2,116	6	0.3			6	0.2
Light-Heavy/Heavy-Heavy	1,093	89	4.4	5 ^(g)	1.0 ^(g)	269 ^(g)	10.7 ^(g)

(a) Includes captive imports - Automobiles: Arrow Champ, Sapporo, Colt, Challenger, Fiesta, and Opel. Trucks: Chevrolet LUV, Ford Courier, Plymouth Arrow, and Dodge D50.

(b) Total does not include some 32,785 special purpose vehicles (AMC Eagle), which are classified with trucks.

(c) Includes federal government vehicles.

(d) Not available.

(e) Shipments only.

(f) Includes vans and special purpose vehicles; also AMC Eagle. Before MY 1980, passenger vans were included with automobile sales data.

(g) Includes heavy-heavy.

TABLE 2.3. Market Shift in Automobile Sales Between 1978 and 1980
(Oak Ridge 1981)

Category	Market Share of Sales (in percent)		
	1978	1979	1980
Two seater	1.2	0.9	2.4
Minicompact	12.8	5.0	4.5
Subcompact	19.9	33.1	38.0
Compact	14.0	9.3	8.0
Mid size	31.6	37.5	33.7
Large	20.8	19.5	13.4

FIGURE 2.7. Survival Probability Curves for Automobiles and Light Trucks
(Oak Ridge 1981)

2.2.2 Capital Stock Information, 2000

Since 1975, several models have been assembled to predict characteristics of the automobile stock and energy use up to the year 2000. Among the organizations performing the modeling were the Office of Technology Assessment, the

TABLE 2.4. Automobiles in Operation, Scrappage Rates, and Vehicle Travel by Age of Vehicle, 1980 (Oak Ridge 1981)

Age (in years)	Number in Operation			Survival Probability ^(a)	Scrappage Rate ^(b)	Percent of Total Vehicle Travel	
	Number in Thousands	Percentage	Cumulative Percentage			Actual	Cumulative
Under 1	5,868	5.6	5.6	99.9	0.1	1.1	1.1
1	10,402	9.9	15.5	99.6	0.3	11.7	12.8
2	10,483	10.0	25.5	99.1	0.5	13.4	26.2
3	9,931	9.5	35.0	98.1	1.1	9.7	35.9
4	8,900	8.5	43.5	96.0	2.1	10.8	46.7
5	6,682	6.4	49.9	92.1	4.0	10.9	57.6
6	8,499	8.1	58.0	85.4	7.3	9.9	67.5
7	9,151	8.8	66.8	75.3	11.8	6.5	74.0
8	7,544	7.2	74.0	62.6	17.0	5.7	79.7
9	5,653	5.4	79.4	49.1	21.5	5.3	85.0
10 and over	<u>21,451</u>	<u>20.6</u>	100.0			<u>15.0</u>	100.0
Total	104,564	100.0				100.0	

(a) The probability that a vehicle of a certain type in a given class will be "in use" (registered) in a given year.

(b) Percentage of vehicles of a certain type in a given age class that are retired from use (lacking registration) in a given year.

Wharton School, Argonne National Laboratory, the DOE Office of Policy Planning and Analysis, the DOT Transportation Systems Center, Oak Ridge National Laboratory, Energy and Environmental Analysis, Inc., and Data Resources, Inc. The results of these projections are shown in Table 2.5. Automobile stock in the year 2000 is projected to range from 131 million vehicles to 153 million vehicles, with the values averaging around 140 million automobiles (see Table 2.5). The annual growth rates ranged from 1.2% to 1.9%.

The Office of Technology Assessment (OTA) developed two scenarios for the changes in Otto and diesel engine use in automobiles. In Case A, the penetration of diesel engines was assumed to be 10% of new car sales in 1985 and 25% of new car sales in 2000. In Case B, the penetration of diesel engines was assumed to be 15% and 40% of new car sales for those same years. Combining these scenarios with an anticipated stock of 112 million autos in 1985 and 140 million autos in 2000 (average values from the forecasts) yields the vehicle and energy-use information given in Table 2.6. In Case A, approximately 110 million of the automobiles would be powered by gasoline engines and in Case B the number would be approximately 96 million. The Case A proportions are in fair agreement with Argonne's (Millar et al. 1982) estimate that 82.4% of the automobile stock in 2000 will be using Otto cycle engines, 17.4% diesel engines, and 0.2% other means of propulsion.

TABLE 2.5. Projections of Automobile Stock in 2000 (Knorr and Millar 1979, Millar et al. 1982)

<u>Source of Projection</u>	<u>Estimated Stock (x 10⁶)</u>
Office of Technology Assessment	148
Jet Propulsion Laboratory	143
Wharton School	146
Argonne National Laboratory	136
Office of Policy Planning and Analysis	131
Transportation Systems Center	136
Oak Ridge National Laboratory	147
Energy and Environmental Analysis, Inc.	133
Data Resources, Inc.	139

TABLE 2.6. Summary of Projected Automobile Ownership, Use, and Energy Demand

	1980	2000	
		Case A	Case B
Automobiles in operation (millions)	104.5	140	140
Automobile vehicle miles traveled (trillions)	1.11	1.69	1.69
Annual new car sales (millions)	8.9	16	16
Percent of Diesels	5	25	40
New car fuel economy (mpg)			
EPA standard(a)	20.0	27.5	35.0
Attained-actual driving	20.4	25.0	29.8
Fleet fuel economy (mpg)			
Attained-actual driving	14.3	24.6	28.0
Annual fleet fuel consumption rate (billions of gallons)			
Gasoline	79.4	56.4	42.9
Diesel	0.6	12.3	17.5
Total	78.0	68.7	60.4
Fleet fuel consumption (millions of barrels per day)	5.1	4.5	3.9

(a) The EPA certification value for a particular car is the weighted average of performance in the EPA urban cycle (55% weight) and rural cycle (45% weight).

Factors that will affect the accuracy of the projections include the penetration of light-duty diesel engines, the price of gasoline, and shifting consumer preference between large and small automobiles.

2.3. FUEL CONSUMPTION DEMAND

2.3.1 Fuel Consumption Demand, 1980

Argonne (Millar et al. 1982) estimates that in 1980 automobiles consumed approximately 77.9 billion gallons of gasoline, or $9,740 \times 10^{12}$ Btu. By comparison, Oak Ridge (1981) estimates 79.4 billion gallons were consumed, or $9,930 \times 10^{12}$ Btu, accounting for 44.3% of the energy used in transportation. The Argonne values will be used here because they appear to be more consistent with other estimates of energy use.

The most recent data available on military automobile energy use indicate that 1.9×10^{12} Btu (15.2 million gallons) of gasoline were used in 1979.

2.3.2 Fuel Consumption Demand, 2000

The OTA scenarios will also be used to project fuel consumption. In Case A, diesel-powered automobiles are assumed to be 10% of new car sales in 1985 and 25% of new car sales in 2000. The EPA fleet fuel economy standard is assumed to rise to 27.5 mpg by 1985 and remain constant until 2000. In Case B, diesel engines are assumed to capture 15% of new car sales in 1985 and 40% by 2000. The EPA fleet fuel economy standard is assumed to increase from 27.5 mpg in 1985 to 35.0 mpg in 2000.

For Case A, the projected automobile gasoline consumption in 2000 is 56.4 billion gallons, or 7.05 quads of gasoline energy. In Case B, the projected consumption is 42.9 billion gallons, or 5.36 quads.

2.4 SERVICE ACTIVITY LEVEL

2.4.1 Service Activity Level, 1980

In 1980, automobiles traveled 1,112 trillion miles, accounting for 83% of the total number of vehicle-miles traveled (VMT) in the transportation sector (Millar et al. 1982, Oak Ridge 1981). On the average, each auto traveled 10,600 miles. Automobiles carried passengers a total of 2,113 trillion miles, accounting for 74% of the domestic passenger-miles traveled (PMT), and consumed 75% of the energy used in domestic passenger travel. The load factor for local travel was 1.87 and for intercity travel was 1.96.

These figures can be translated to engine load-miles to provide a measure of the work being performed by the engine. In 1980 the curb weight of the average automobile was 3363 lb (Abarcar, Hane and Johnson 1984). If a typical load factor was 1.9 for passengers (averaging 150 lb) and a typical cargo weight was 50 lb, the average gross weight totals to 3698 lb. This weight multiplied by the approximately 1,112 trillion miles traveled by automobiles yields a value of 2.06 trillion ton-miles, or 19,700 ton-miles per vehicle.

2.4.2. Service Activity Level, 2000

An average of the forecasts mentioned earlier indicates that the number of vehicle-miles traveled in 2000 will increase to 1.69 trillion miles. The average annual VMT is forecasted to increase slightly, to 12,100 miles. In Scenario A, approximately 80% of the automobiles are gasoline-powered and in Case B, 69% of the automobiles use gasoline. Unfortunately, the OTA assumptions regarding changes in the average weight of the vehicles in both scenarios were not presented. However, a minimal average weight reduction of 500 lb seems reasonable and will be used for the Scenario A approximation. Assuming that much of the improvement in gasoline fuel economy for Scenario B will also be attributable to weight reduction, the average weight will be further reduced to 2360 lb. Assuming the passenger and cargo loads remain relatively unchanged, the engine load-miles can be approximated as 1.91 trillion ton-miles (17,300 ton-miles per vehicle) for Scenario A and 1.37 trillion ton-miles (14,300 ton-miles per vehicle) for Scenario B.

3.0 LIGHT TRUCKS

The entire trucking sector consumes 22.5% of the gasoline used in transportation. Light trucks are those with a gross vehicle weight (GVW) of less than 10,000 lb. Medium trucks range from 10,001 lb to 19,500 lb GVW; light-heavy trucks range from 19,501 lb to 26,000 lb GVW; and heavy-heavy trucks are those over 26,001 lb GVW. In some instances, the categories of trucks are further disaggregated into eight weight classes, with light trucks occupying weight classes 1 and 2. These weight classes and their weight ranges are shown in Table 3.1.

TABLE 3.1. Truck Categories by Vehicle Weight (JFA 1976)

<u>Size Class</u>	<u>Number</u>	<u>Weight Class Gross Vehicle Weight (lb)</u>
Light	1	6,000
	2	6,000-10,000
Medium	3	10,000-14,000
	4	14,000-16,000
	5	16,000-19,500
Light-Heavy	6	19,500-26,000
Heavy-Heavy	7	26,000-33,000
	8	over 33,000

As the size of the trucks increases, there is a marked shift from Otto cycle, gasoline-powered engines to diesel cycle engines. Thus, while the medium and heavy trucks consumed 80% as much energy as the light trucks, most of this energy was in the form of diesel fuel. A large proportion of light trucks is also used for recreational purposes; larger vehicles are not commonly used for recreation. Light trucks, therefore, possess energy and end-use characteristics that are notably different from the larger categories. It has been common practice in previous studies to group light trucks together with automobiles because of the similarity in engine size and loads.

However, data from the Jack Faucett Associates study (1976), the Oak Ridge transportation data base (1981), and the Argonne data base (Millar et al. 1982) have presented separate information on automobiles and light trucks. Because of the differences between light trucks and heavier trucks and the convenient availability of disaggregated information, light trucks will be discussed separately.

Light trucks account for 85% of the vehicles in the trucking sector and consume 87% of the gasoline. The Otto cycle engines used in these trucks burn both gasoline and liquefied petroleum gas (LPG). However, LPG fuel is used in only 0.34% as many vehicles as gasoline.

The most comprehensive study in this area appears to be that performed by JFA, Trucking Activity and Fuel Consumption 1973, 1980, 1985, and 1990 (1976). The primary limitations of this study are that it was done eight years ago and that it reviews civilian consumption only. However, data for 1980 and projections can be compared with the Oak Ridge transportation data book and the Argonne data book, which are less thorough but are much more up-to-date. These three studies form the primary references for the information presented in this chapter on light trucks and in the following chapter on medium and heavy trucks. Other sources of information include the Federal Highway Administration statistics on all trucks and the Project Independence report, which combined personal trucks with personal automobiles.

3.1 EFFICIENCY ESTIMATE

The thermodynamic characteristics of light truck gasoline engines are essentially the same as automobile engines, hence, their delivered, or brake, thermal efficiency is approximately the same. For a discussion of these characteristics see Section 2.1. However, because of the larger sizes and weights typical of light trucks, their fuel economy is worse.

Argonne (Millar et al. 1982) has compiled estimated values of average fuel economy in light trucks from a number of sources. These are presented in Table 3.2. The average of these estimates for fuel economy in 1980 is 12.4 mpg.

TABLE 3.2. Comparison of Fuel Economy Estimates for Light Trucks in 1980 (Millar et al. 1982)

<u>Source of Estimate</u>	<u>Fuel Economy (mpg)</u>
Oak Ridge National Laboratory	13.8
Argonne National Laboratory	12.7
Office of Policy Planning and Analysis	12.1
Transportation Systems Center	14.1
Energy and Environmental Analysis, Inc.	10.6
Data Resources, Inc.	10.9

3.2 CAPITAL STOCK INFORMATION

3.2.1 Capital Stock Information, 1980

The number of light trucks in use in 1980 has been estimated by several sources and is shown in Table 3.3. These values are for all light trucks, both civilian and government, unless otherwise noted. Oak Ridge notes in their estimates that 99.6% of light civilian trucks in operation are powered by gasoline. LPG is used in a little more than 0.3% and diesel fuel in the remainder.

TABLE 3.3. Comparison of Stock Projections for Light Trucks (Millar et al. 1982, Knorr and Millar 1979, Oak Ridge 1981)

<u>Source of Projection</u>	<u>Stock (10⁶)</u>		<u>Avg. Annual % Change</u>
	<u>1980</u>	<u>2000</u>	
Oak Ridge National Laboratory ^(a)	30.12	--	
Argonne National Laboratory	28.7	41.7	1.9
Office of Policy Planning and Analysis	28	47	2.6
Energy and Environmental Analysis, Inc.	29.1	49.7	2.7
Data Resources, Inc.	30.1	42.3	1.7
Lidsey-Kaufman	29	42	1.8

(a) Civilian consumption only.

For this study, we will use a capital stock of 29 million light trucks, 87,000 of which are powered by LPG. The total number of diesel light trucks was less than 0.1%.

JFA (1976) estimated that in 1973 there were 980,000 government trucks, most of which were light trucks. If the government truck stock increased at the same rate as the civilian truck stock, there would be approximately 1,560,000 government trucks in use in 1980. However, because the popularity of light trucks for personal recreation was the primary reason for the growth in the nongovernment sector, it is not likely that federal growth kept pace with private growth. The size of the government truck fleet is thus likely to be somewhere between 980,000 and 1,560,000 vehicles. A mean value of 1,270,000 vehicles may be a reasonable estimate.

Oak Ridge has estimated that 2,245,000 new light trucks were sold in 1980. Assuming that 5% of these sales were diesel engine vehicles, 2,133,000 new Otto cycle light trucks were purchased in 1980.

The survival curve for light trucks is slightly more extended than that for automobiles. As seen in Figure 2.7, approximately half of the trucks are still in use after 15 years. By comparison, the "half-life" for automobiles is 10 years.

3.2.2 Capital Stock Information, 2000

Because of the similarity in energy and end-use between light trucks and automobiles, several projections of the change in light truck stock to the year 2000 have been made. Table 3.3 shows the results of several models, with stock projections ranging from 42 million to 49.7 million vehicles.

Using a stock of 29 million vehicles in 1980 and an average 2% growth rate, the projected light-duty vehicle stock in 2000 is 43 million. Assuming that diesel engines are used in 20% of the trucks in operation by 2000, the Otto cycle light truck stock is 34.4 million vehicles. Further assuming that the number of LPG vehicles remains proportionate, 33.3 million vehicles would be powered by gasoline and 108,000 by LPG.

3.3 FUEL CONSUMPTION DEMAND

3.3.1 Fuel Consumption Demand, 1980

Estimates of energy consumption in 1980 and the year 2000 have also been compiled by Argonne and Oak Ridge. These estimates are shown in Table 3.4, along with estimates from the DOT Transportation Systems Center, and another study at Oak Ridge, Energy Savings Impacts of DOE's Conservation and Solar Programs, (Greene et al. 1981).

TABLE 3.4. Comparison of Energy-Use Projections for Light Trucks (Millar et al. 1982, Knorr and Millar 1979, Oak Ridge 1981)

<u>Source of Projection</u>	<u>Gasoline Energy Use (quads)</u>		<u>Avg. Annual % Change</u>
	<u>1980</u>	<u>2000</u>	
Oak Ridge National Laboratory ^(a)	2.6	--	
Argonne National Laboratory	2.71	2.63	(-0.2)
Office of Policy Planning and Analysis	2.5	3.1	1.1
Energy and Environmental Analysis, Inc.	3.34	3.19	(-0.2)
Transportation Systems Center	2.43	1.73	(-1.73)
Oak Ridge National Laboratory (Samuels 1981)	2.7	4.1	(2.3)

(a) Civilian light trucks only.

When the 128×10^{12} Btu of gasoline consumed by government light trucks is added to the Oak Ridge estimate of 2.6 quads in 1980, the Argonne and Oak Ridge values become nearly identical. This study will use this value of 2.71 quads in 1980. In addition to this gasoline, approximately 7.25×10^{12} Btu of LPG was used in light trucks.

JFA projected that between 1973 and 1980 the total amount of gasoline consumed would increase from 21,900 million gallons to 29,500 million gallons, at an annual growth of 4.4%. Oak Ridge and Argonne data for 1980 show that gasoline consumption was only 21,700 million gallons, which would be equivalent to

a 0.1% annual decrease. The 23% shortfall is likely to be at least in part due to the dramatic increase in gasoline prices between 1973 and 1980. It also points to the difficulty in making accurate projections.

3.3.2 Fuel Consumption Demand, 2000

Table 3.4 also shows estimates of energy consumption by light trucks in 2000. The projections can be seen to vary widely between a low of 1.73 quads predicted by the Transportation Systems Center and a high of 4.1 quads predicted by Oak Ridge (Greene et al. 1981). The average annual growth rates are seen to range from 2.3% to -1.73%.

This study will assume that a small growth of 0.2% annually will occur, that diesels will account for 20% of the energy use, and that the use of LPG remains proportionate. Using these assumptions, the projected consumption of gasoline by light trucks in 2000 will be 2.82 quads, and 7.55×10^{12} Btu will be consumed in the form of LPG.

3.4. SERVICE ACTIVITY LEVEL

3.4.1 Service Activity Level, 1980

The Oak Ridge (1981) study estimates that the primary use of light trucks in 1980 was for personal transportation. In 1977, this was the primary use for 55% of the light trucks in operation. Excluding government trucks, the major uses and their distribution among light trucks were as follows:

Agriculture	12.7 %
Construction	8.5 %
Manufacturing	1.3 %
Wholesale trade	3.9 %
Retail trade	5.1 %
For hire	0.7 %
Utilities	2.3 %
Services	7.9 %
Personal transportation	55.2 %
Other	<u>2.2 %</u>
Total	100.0 %

This distribution is in general agreement with similar information published by Argonne for the use of light trucks in 1975. Argonne further projected changes in use out to the year 2000 and their results will be discussed below.

Estimates and projections of light truck use for 1980 and 2000 have been assembled by Argonne, Oak Ridge, and JFA. These figures for 1980 range from a low of 8,700 vehicle-miles traveled (VMT) to 11,900 VMT. For this study we will use Argonne's value of 9,600 VMT, which is in the middle of the various estimates.

JFA has estimated an average vehicle load and vehicle weight for light trucks. Combining this load (0.28 tons) and weight (2.88 tons) with the stock and VMT information yields a total service of 877×10^9 ton-miles for gasoline vehicles and 2.6×10^9 ton-miles for LPG vehicles.

3.4.2 Service Activity Level, 2000

Table 3.5 shows projections from an Argonne model for the change in the use of light trucks between 1975 and 2000 for various services.

TABLE 3.5. Projected Changes in the Use of Light Trucks
(Knorr and Millar 1979)

<u>Use Sector</u>	<u>Projected Light Trucks 10⁶ Trucks</u>		<u>Percent Change</u>
	<u>1975</u>	<u>2000</u>	
Personal	11.3	27.0	139
Service/Utility	2.1	7.3	248
Agriculture	3.0	4.0	33
Manufacturing	0.3	0.8	167
Government	1.0	1.5	56
Wholesale/Retail	0.9	1.9	11
Other	<u>1.4</u>	<u>1.8</u>	<u>29</u>
Total	20.0	44.3	117

Information describing the manner in which these changes in light truck use (such as the number of ton-miles) will affect service measures was not provided by the model results. However, estimates of the change in VMT to 2000 are available. Average annual growth estimates range from 0.1% to 0.9%. Argonne estimated an average growth of 0.3% annually, and because it is in the middle range of the projections, it will be used here. The average annual VMT in 2000 is therefore expected to increase to 10,100 miles. Assuming that the average vehicle weight and load remain constant, the projected service in 2000 is $1,063 \times 10^9$ ton-miles for gasoline vehicles and 3.62×10^9 ton-miles for light trucks fueled by LPG.

4.0 MEDIUM AND HEAVY TRUCKS

Trucks that are heavier than 10,000 lb GVM are classified as medium, light-heavy, or heavy-heavy trucks. Recall from Table 3.1 that these trucks compose the larger six weight classes of the eight that are used to categorize trucks. Though medium, light-heavy, and heavy-heavy trucks compose only 15% of the total number of vehicles in the trucking sector, they consumed nearly 45% of the energy. This energy was supplied as either diesel fuel, gasoline, or LPG.

As the size of the trucks increases, so does the tendency to use a diesel cycle engine rather than an Otto cycle engine. This shift occurs because the unthrottled diesel engine has a higher efficiency, because diesel fuel has approximately 10% more energy per volume than gasoline, and because the heavier weight of the diesel engine is not as great a penalty with larger trucks as it is with lighter vehicles. As a consequence of this preference for diesel engines, 80% of the energy used by medium and heavy trucks is in the form of diesel fuel, 19% is gasoline, and less than 1% is LPG. The primary sources of information regarding medium and heavy trucks are the same as those for light trucks: JFA (1976), Oak Ridge (1981) and Argonne (Millar et al. 1982) (see Chapter 3).

4.1 EFFICIENCY ESTIMATES

The thermodynamic characteristics of truck Otto cycle engines are essentially the same as automobile engines; hence, their delivered, or brake thermal efficiency is approximately the same. For a discussion of these characteristics see Section 2.1. It is important to remember that the fuel economy of the vehicle can be strongly influenced by changes other than those related to the engine. For example, wind deflectors placed on top of the cab and in front of the trailer can reduce fuel consumption by 5%.

Jack Faucett (JFA), A. D. Little (ADL), and the American Transportation Association (ATA) estimated the average fuel economy in 1975 for each of the eight truck weight classes. These estimates for medium and heavy trucks are

shown in Table 4.1. The variation in fuel economy as a function of the gross vehicle weight is shown in Figure 4.1.

TABLE 4.1. Comparison of Truck Fuel Economy by Gross Vehicle Weight (JFA 1976)

<u>Gross Vehicle Weight Class</u>	<u>Local, Gasoline (mpg)</u>		
	<u>ADL</u>	<u>ATA</u>	<u>JFA</u>
3	8.3	7.08	8.96
4	6.8		7.86
5	5.8		6.86
6	5.7	5.81	5.53
7	5.3	5.32	4.09
8	4.9		3.76

4.2 CAPITAL STOCK INFORMATION

4.2.1 Capital Stock Information, 1980

Several organizations have estimated the medium and heavy-duty truck stock in 1980. These estimates include both Otto and diesel engine trucks and are summarized in Table 4.2. The aggregated and the disaggregated stock information provided by Oak Ridge and Argonne are generally very close; however, since more detailed information and projections are available from Argonne, their numbers will be used in this report. The Argonne estimates and projections of Otto cycle truck stock are shown in Table 4.3. Gasoline is used in 99.7% of these engines, with LPG used in the remainder.

Oak Ridge has estimated the sales of domestic and imported trucks for 1980. These sales figures are shown in Table 4.4.

Information describing the percent of sales that were Otto cycle versus diesel cycle engines was not given in the Oak Ridge study. To estimate these values, data from the Argonne study were used. An estimate for Otto cycle

FIGURE 4.1. Fuel Consumption Rates for Local Gasoline-Powered Vehicles by Gross Vehicle Weight Rating (JFA 1976)

TABLE 4.2. Comparison of Stock Projections for All Medium and Heavy Trucks (Millar et al. 1982)

Source of Projection	Stock (10 ⁶)		Avg. Annual % Change
	1980	2000	
Oak Ridge National Laboratory	5.15		
Argonne National Laboratory	5.31	8.61	2.4
Oak Ridge National Laboratory ^(a)	7.16	12.68	2.9
Office of Policy Planning and Analysis	4.5	5.2	0.8
Energy and Environmental Analysis, Inc.	4.45	4.97	0.6
Data Resources, Inc.	4.7	5.5	0.5

(a) Oak Ridge estimate (Greene et al. 1981).

TABLE 4.3. Estimated and Projected Otto Engine Truck Stock by Size Category (Millar et al. 1982)

<u>Size Category</u>	<u>Stock (thousands)</u>		<u>Avg. Annual % Change</u>
	<u>1980</u>	<u>2000</u>	
Medium	2,085	2,166	0.2%
Light-heavy	1,255	1,129	-0.5%
Heavy-heavy	<u>246</u>	<u>7.6</u>	<u>-16%</u>
Total	3,586	3,303	-0.4%

TABLE 4.4. Domestic and Imported Truck Sales in 1980^(a) (Oak Ridge 1981)

<u>Trucks</u>	<u>Domestic Sales</u>	<u>Imported Sales^(a)</u>
Medium	6,000	--
Light-heavy	89,000	5,000
Heavy-heavy	175,000	

(a) Includes captive imports.

truck sales can be made by assuming that the change in gasoline truck stock is reflected by the sales and by assuming a 4% retirement rate. The estimated sales are shown in Table 4.5. The preference for diesel engines in heavy-heavy trucks is assumed to be near 100%, therefore Otto engine sales in this category were estimated to be minimal.

TABLE 4.5. Estimated Otto Cycle Truck Sales in 1980

<u>Trucks</u>	<u>Sales</u>
Medium	5,850
Light-heavy	82,600
Heavy-heavy	53,000

4.2.2 Capital Stock Information, 2000

The projected changes in total truck stock by 2000 are also shown in Table 4.2. The overall average annual growth rate estimates range from 0.5% to 2.9% with resultant stock estimates ranging from 4,970,000 to 12,680,000 trucks. The Argonne values will be used here because their projections are in the middle of the range and because the most detailed information is available from this source. Estimates of the Otto cycle truck stock by size category have been provided in Table 4.3. These data agree well with an in-house evaluation that applied JFA projections to Oak Ridge stock information. As the table indicates, Argonne predicts that trucks in the heavy-heavy category will be almost entirely diesel-powered in 2000.

4.3 FUEL CONSUMPTION DEMAND

4.3.1 Fuel Consumption Demand, 1980

The energy used by medium- and heavy-duty trucks has been estimated by several organizations and is summarized in Table 4.6. Argonne and Oak Ridge provide nearly identical estimates of total energy use, though their estimates of gasoline consumption vary by a factor of two. Oak Ridge (1981) estimates that approximately 400×10^{12} Btu of gasoline and 4.0×10^{12} Btu of LPG were

TABLE 4.6. Comparison of Energy-Use Projections for Medium and Heavy Trucks (Millar et al. 1982)

<u>Source of Projection</u>	<u>Energy Use (quads)</u>		<u>Avg. Annual % Change</u>
	<u>1980</u>	<u>2000</u>	
Oak Ridge National Laboratory	2.01		
Argonne National Laboratory	2.01	3.15	2.3
Oak Ridge National Laboratory ^(a)	3.3	4.8	1.9
Office of Policy Planning and Analysis	2.3	3.0	1.3
Energy and Environmental Analysis, Inc.	2.33	2.95	1.2
Transportation Systems Center	2.31	2.98	1.3

(a) Oak Ridge estimate (Greene et al. 1981).

consumed in this category; Argonne (Millar et al. 1982) estimates that 900×10^{12} Btu of gasoline was consumed. The reason for this difference is not clear, since the vehicle stock estimates are similar. This study will use a mean value of 650×10^{12} Btu for gasoline consumption and 4.0×10^{12} Btu for LPG.

Gasoline consumption data by truck size categories were not directly available. A combination of Argonne, Oak Ridge, and JFA information yields the estimates shown in Table 4.7.

TABLE 4.7. Otto Engine Truck Energy Consumption in 1980

<u>Size Category</u>	<u>Energy Consumption (Gasoline & LPG, $\times 10^{12}$ Btu)</u>	<u>Percent of Total</u>
Medium	228	35
Light-heavy	293	45
Heavy-heavy	130	20

4.3.2 Fuel Consumption Demand, 2000

Projections of total energy use in the year 2000 are also given in Table 4.6. Unfortunately, direct estimates of gasoline consumption were not provided. If we use the Argonne stock data and assume that changes in gasoline consumption roughly parallel changes in Otto engine stock, then approximately 600×10^{12} Btu of gasoline will be consumed in 2000. This estimate agrees with a similar analysis of JFA projections. Again, assuming that Otto engine fuel economy is largely unchanged, the projections show 590×10^{12} Btu of gasoline and 4.4×10^{12} Btu of LPG used. This study will estimate consumption at 600×10^{12} Btu of gasoline and 4.4×10^{12} Btu of LPG.

If the change in energy use in the size categories parallels the change in truck stock, then the energy use in each category would be as shown in Table 4.8.

TABLE 4.8. Projected Otto Engine Truck Energy Consumption in 2000

<u>Size Category</u>	<u>Energy Consumption (Gasoline & LPG, x 10¹² Btu)</u>	<u>Percent of Total</u>
Medium	237	47
Light-heavy	265	52
Heavy-heavy	4.0	1

4.4 SERVICE ACTIVITY LEVEL

4.4.1 Service Activity Level, 1980

JFA has estimated several characteristics of Otto cycle truck activity for 1980 for each of the eight weight classes. They have analyzed the activity of trucks by the type of fuel, type of travel (intercity or local) and by weight class. Their results show that on the average gasoline-fueled trucks travel less than their diesel counterparts. Estimates regarding the average annual miles per vehicle, total vehicle-miles, average vehicle load, and total ton-miles are included.

Combining JFA's activity estimates with the stock information developed earlier yields the activity characteristics shown in Table 4.9.

Oak Ridge has compiled information on the major uses of medium and heavy trucks. The categories of end use reviewed include agriculture, construction, manufacturing, wholesale trade, retail trade, for hire, utilities, services, personal transportation, and others. The distribution of truck use among these categories in 1977 is shown in Table 4.10.

4.4.2 Service Activity Level, 2000

Projected changes to 2000 in the overall number of vehicle-miles traveled have been summarized by Argonne (Millar et al. 1982). These estimates of average annual growth range from -0.5% to 2.7%. Because of the anticipated growth of diesel engine use, much of this growth is likely to occur with diesel-fueled trucks. However, specific descriptions of the projected growth in gasoline versus diesel trucks were not given. Assuming that the average service of

TABLE 4.9. Activity for Gasoline-Fueled Trucks in 1980

<u>Average Vehicle Miles</u>	<u>Truck Size Class</u>		
	<u>Medium</u>	<u>Light-heavy</u>	<u>Heavy-heavy</u>
Stock of Vehicles (thousands)	2,085	1,255	246
Average Annual Miles per Vehicle	11,740	10,170	15,590
Total Vehicle Miles (millions)	24,480	12,770	3,840
Average Vehicle Load (tons)	0.96	1.58	3.61
Average Total Weight (tons)	3.82	6.26	12.6
Total Ton-Miles (millions)	93,500	79,900	48,400

gasoline trucks remains unchanged, and that changes in activity are primarily a function of changes in stock, the projected activity in 2000 is as shown in Table 4.11.

TABLE 4.10. Percentage Distribution of Truck Energy Consumption by Major Use and Size Class, 1977^(a) (Oak Ridge 1981)

Major Use	Size Class ^(b)				Total
	Light	Medium	Light-heavy	Heavy- ^(c) heavy	
Column percents					
Agriculture	12.7	14.5	13.6	6.6	10.8
Construction	8.5	8.9	11.1	10.0	9.2
Manufacturing	1.3	4.6	5.2	10.6	4.8
Wholesale trade	3.9	20.7	24.8	13.6	9.1
Retail trade	5.1	12.5	14.3	5.8	6.1
For hire	0.7	8.9	11.1	41.9	15.6
Utilities	2.3	4.1	4.2	0.7	2.0
Services	7.9	11.8	7.1	2.2	6.2
Personal trans- portation	55.2	5.6	0.1	(d)	31.3
Other	<u>2.2</u>	<u>8.4</u>	<u>8.6</u>	<u>8.7</u>	<u>5.1</u>
Total	100.0	100.0	100.0	100.0	100.0
Row percents					
Agriculture	66.2	8.1	5.1	20.6	100.0
Construction	52.2	5.8	4.9	37.0	100.0
Manufacturing	15.1	5.8	4.4	74.7	100.0
Wholesale trade	24.2	13.7	11.1	50.9	100.0
Retail trade	46.6	12.2	9.5	31.7	100.0
For hire	2.6	3.4	2.9	91.1	100.0
Utilities	67.0	12.4	8.8	11.7	100.0
Services	71.9	11.4	4.6	12.0	100.0
Personal trans- portation	98.9	1.1	(d)	(d)	100.0
Other	24.8	9.9	6.9	58.3	100.0
Percent of Total Energy Consumption	56.1	6.0	4.1	33.9	100.0

(a) Government trucks not included.

(b) These size classes are based on the actual average gross vehicle weight ratings of trucks during the year prior to the survey and do not necessarily correspond to the manufacturers' suggested gross vehicle weight rating.

Truck size classes: Light - Classes 1 and 2 (0-10,000 lb GVW);

Medium - Classes 3 through 5 (10,001-19,500 lb GVW);

Light-heavy - Class 6 (19,501-26,000 lb GVW);

Heavy-heavy - Classes 7 and 8 (26,001 lb GVW or more).

(c) Heavy-heavy trucks appear to have been undercounted, therefore the energy-use estimates may be low.

(d) Negligible.

TABLE 4.11. Activity for Gasoline- and LPG-Fueled Trucks in 2000

<u>Average Vehicle-Miles</u>	<u>Truck Size Class</u>		
	<u>Medium</u>	<u>Light-heavy</u>	<u>Heavy-heavy</u>
Stock of Vehicles (thousands)	2,166	1,129	7.6
Average Annual Miles per Vehicle	11,740	10,170	15,590
Total Vehicle-Miles (millions)	25,240	11,480	119
Average Vehicle Load (tons)	0.96	1.58	3.61
Average Total Weight (tons)	3.82	6.26	12.6
Total Ton-Miles (millions)	96,400	71,900	1,500

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