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ECUT Energy Data Reference Series: Otto Cycle Engines in Transportation

G. J. Hane

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July 1984

Prepared for the U.S. Department of Energy under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory

Operated for the U.S. Department of Energy by Battelle Memorial Institute

Battelle

PNL-5191

PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC06-76RLO 1830

Printed in the United States of America
Available from
National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

NTIS Price Codes
Microfiche A01

Printed Copy

Pages	Price Codes
001-025	A02
026-050	A03
051-075	A04
076-100	A05
101-125	A06
126-150	A07
151-175	A08
176-200	A09
201-225	A010
226-250	A011
251-275	A012
276-300	A013

PNL-5191
UC-95

ECUT ENERGY DATA REFERENCE SERIES:
OTTO CYCLE ENGINES IN TRANSPORTATION

G. J. Hane
D. R. Johnson

July 1984

Prepared for
Energy Conversion and Utilization
Technologies Division
Office of Energy Systems Research
Conversation and Renewable Energy
U.S. Department of Energy
under Contract DE ACD6-76RLO 1830

Pacific Northwest Laboratory
Richland, Washington 99352

ACKNOWLEDGMENTS

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 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, 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 on engine combustion systems technology. The objective of this R&D is to develop and accelerate the application of new combustion technologies that can be used by engine designers to improve fuel efficiency, to maintain environmental acceptability, and to ease the transition to alternative fuels. This volume explores the potential for the results of this research to be applied to transportation modes that use Otto cycle engines.

Other volumes in the ECUT Energy Data Reference Series include:

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.

Abarcar, R. B., G. J. Hane and D. R. Johnson. ECUT Energy Data Reference Series: High-Temperature Materials for Advanced Heat Engines. PNL-5193, 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. De Bellis. 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 Otto cycle engines in transportation. The transportation modes discussed in this report include the following:

- automobiles
- light trucks
- heavy trucks
- marine
- recreational vehicles
- motorcycles
- buses
- aircraft
- snowmobiles.

These modes account for nearly 100% of the gasoline and LPG consumed in transportation engines.

The information provided on each of these modes includes descriptions of the average energy conversion efficiency of the engine, the capital stock, the amount of energy used, and the activity level as measured in ton-miles. Estimates are provided for the years 1980 and 2000. 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 1980	# Unit Process Hardware Systems 1980	# Unit Process Hardware Systems 2000	Fuel Consumption Demand (Btu) 1980	Fuel Consumption Demand (Btu) 2000	Product or Service Activity Level (ton-miles) 1980	Product or Service Activity Level (ton-miles) 2000
AUTOMOBILES							
Gasoline	26%	104,564,000	110,000,000	$9,740 \times 10^{12}$	$7,050 \times 10^{12}$	$2,060 \times 10^{9}$	$1,910 \times 10^{9}$
LIGHT TRUCKS							
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
MEDIUM AND HEAVY TRUCKS							
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}
MARINE							
Gasoline-outboard	19%	7,440,000	11,250,000	132×10^{12}	169×10^{12}	--	--
Gasoline-inboard	26%	1,860,000	3,750,000	88×10^{12}	169×10^{12}	--	--
RECREATIONAL VEHICLES							
Gasoline	26%	6,000,000	--	87.8×10^{12}	--	64.4×10^{9}	--
MOTORCYCLES							
Gasoline	26%	7,035,500 (1979)	--	65.9×10^{12} (1981)	--	7.60×10^{9}	--
BUSES							
Gasoline	26%	390,000	306,000	50×10^{12}	33×10^{12}	24.7×10^{9}	16.4×10^{9}
AIRCRAFT							
Aviation Gasoline	30%	189,210	--	68.8×10^{12}	--	--	--
SNOWMOBILES							
Gasoline	19%	1,880,000 (1978)	--	40.4×10^{12}	--	--	--

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 Expansion (Increased Service Demand) 2000	# UPHS Due to Replacement of Obsolete Units 2000	# UPHS from 1980 Remaining In Service 2000
AUTOMOBILES					
Gasoline	104,564,000	110,000,000	5,436,000	101,427,000	3,136,920
LIGHT TRUCKS					
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
MEDIUM AND HEAVY TRUCKS					
Gasoline	3,575,000	3,293,000	--	2,399,000	894,000
LPG	10,760	9,930	--	7,240	2,690
MARINE					
Gasoline-outboard	7,440,000	11,250,000	3.81×10^6	--	--
Gasoline-Inboard	1,860,000	3,750,000	1.89×10^6	--	--
RECREATIONAL VEHICLES					
Gasoline	6,000,000	--	--	--	--
MOTORCYCLES					
Gasoline	7,035,500 (1979)	--	--	--	--
BUSES					
Gasoline	390,000	306,000	--	208,500	97,500
AIRCRAFT					
Aviation Gasoline	189,210	--	--	--	--
SNOWMOBILES					
Gasoline	1,880,000 (1978)	--	--	--	--

CONTENTS

FIGURES

TABLES

1.0 ENERGY-USE AND CAPITAL STOCK INFORMATION

The objective of this effort is to provide information on the use of Otto cycle engines in the transportation sector. This information will be used to support program planning for the Energy Conversion and Utilization Technology division of the U.S. Department of Energy.

Currently, the only two fuels that are being used to measurable extent in Otto cycle transportation engines are gasoline and liquefied petroleum gas (LPG). Because more than 99.9% of the fuel used in Otto cycle engines is gasoline, discussion will center around the consumption of this fuel in the various modes of transportation. Liquefied petroleum gas composes most of the remaining 0.1%.

The percentage of total gasoline used in transportation in 1979 is given below by transportation mode (Oak Ridge 1981):

automobiles	73.6%
trucks	22.5%
marine	1.5%
recreational vehicles	0.7%
motorcycles	0.5%
buses	0.4%
aircraft	0.4%
snowmobiles	0.3%
military	0.2%
Total	100.0%

The first three modes, automobiles, trucks, and marine, account for 97.6% of the gasoline used in transportation and will be discussed in the most detail. Because the remaining modes account for only 2.4% of the gasoline used in transportation, they will not be analyzed as thoroughly.

Information provided on these transportation modes includes: 1) energy-use efficiency information, 2) capital stock data, 3) energy-use data, and 4) end-use service information. The information is provided for 1980 and, where possible, projected out to the year 2000.

There are two Otto cycle technologies used in transportation that convert fuel energy to work. These technologies are the four-stroke and two-stroke engines. The four-stroke engine is by far the dominant technology used in transportation. It is used exclusively in all the major transportation modes except marine transportation, motorcycles, and snowmobiles. Most engineering analysis of four-stroke engines has been related to the automobile engine. Because automobiles are also the largest energy-using mode, and because the automobile engine is representative of the four-stroke engines used in the other modes of transportation, the efficiency characteristics of four-stroke engines will be analyzed in the chapter describing automobile transportation.

Because the primary use of the two-stroke engine is in outboard motors for recreational vehicles, the discussion of the efficiency characteristics of the two-stroke engine will be presented in the chapter on marine transportation. Pollution emissions standards have drastically reduced the use of two-stroke engines in motorcycles.

Information on fuel economy, capital stock, energy use, and end-use service was derived from a number of sources. The most comprehensive and up-to-date sources are the Transportation Energy Conversation Data Book: Edition 5 published by the Oak Ridge National Laboratory (1981) and Baseline Projections of Transportation Energy Consumption By Mode by the Argonne National Laboratory (Millar et al. 1982). These data books summarized information from a large number of sources; many of these sources have been used to provide additional detail for this report. Each of these sources will be discussed in the relevant sections.

2.0 AUTOMOBILES

Automobiles compose the largest energy-consuming mode of the transportation end-use sector, accounting for 49.3% of the energy and 73.6% of the gasoline used in this sector in 1980. Though the primary fuel used by automobiles is gasoline, in recent years diesel engines have become increasingly popular because of their greater fuel economy. In 1980, diesels accounted for 5% of new car sales. Though this percentage is still small, it has been estimated that diesels will compose 25% of new car sales in the year 2000 (OTA 1979).

Automobiles are typically classified according to six size categories: 1) two seater, 2) minicompact, 3) subcompact, 4) compact, 5) midsize, and 6) large. The boundaries defining these categories are not clear. However, since data are available in this form, these categories will be used in this discussion.

As mentioned in the introduction, essentially all of the automobile engines in use are four-stroke engines. The engine efficiency characteristics of the automobile engine are also the most thoroughly explored of the four-stroke Otto engines. Therefore, the discussion of four-stroke Otto cycle efficiency will center around the automobile engine and will be included in Section 2.1.

The most recent and comprehensive sources of information describing automobile stock, activity, and energy use are the Transportation Energy Conservation Data Book: Edition 5 compiled by the Oak Ridge National Laboratory (1981), and Baseline Projections of Transportation Energy Consumption By Mode by the Argonne National Laboratory (Millar et al. 1982). The fuel consumption, capital stock and activity data are summarized at the end of this section in Tables 2.8 and 2.9.

2.1 EFFICIENCY ESTIMATE

A large number of factors contribute to the efficiency of automobile transportation. These factors include the thermodynamic characteristics of the engine, parasitic mechanical losses, road and aerodynamic frictional effects, and the weight of the vehicle. The factors that contribute to engine and vehicle inefficiency are shown in Figure 2.1. The first two levels in the hierarchy of losses illustrated in Figure 2.1 are attributable to thermodynamic limits and engine losses. Levels 3 and 4 describe the nonengine-related losses that also contribute to the ultimate efficiency value of the transportation service.

The figure shows that, typically, over 60% of the available work from the fuel is lost immediately through the engine exhaust and through engine cooling. Only 38% of the fuel energy remains to perform work on the piston. This is normally termed the indicated efficiency of the engine.

Other engine losses occur between the work done on the piston and the work done on the output shaft. These losses are shown in level 2 of Figure 2.1. The figure shows that an additional 6% of absolute efficiency is lost to air pumping and 7% of absolute efficiency is lost to the frictional effects. The output shaft efficiency, normally termed the brake thermal efficiency, is consequently reduced to 26%.

The direct injection stratified charge and dilute homogeneous charge engines, which are being researched by the Engine Combustion Technology program within ECUT, directly address one of these losses and indirectly address another. These advanced engine concepts achieve load control by varying the fuel/air ratio and thus would eliminate the throttling loss that is the primary contribution to the air pumping loss. Eliminating throttling loss would result in a 20% to 25% relative increase in brake thermal efficiency.

The efficiency advantages of an overall lean mixture can be exploited by varying the fuel/air ratio to achieve load control. Current engines use a stoichiometric or near-stoichiometric mixture, which limits the theoretical fuel/air cycle efficiency to approximately 46%. Cylinder wall heat loss, exhaust blowdown loss, and finite speed loss reduce this efficiency to the indicated efficiency of 38% (shown in Figure 2.1). As the fuel/air ratio is decreased from its stoichiometric value, the theoretical fuel/air cycle efficiency increases, thus increasing the indicated efficiency. The precise degree of this increase over a typical driving cycle is, however, an open question.

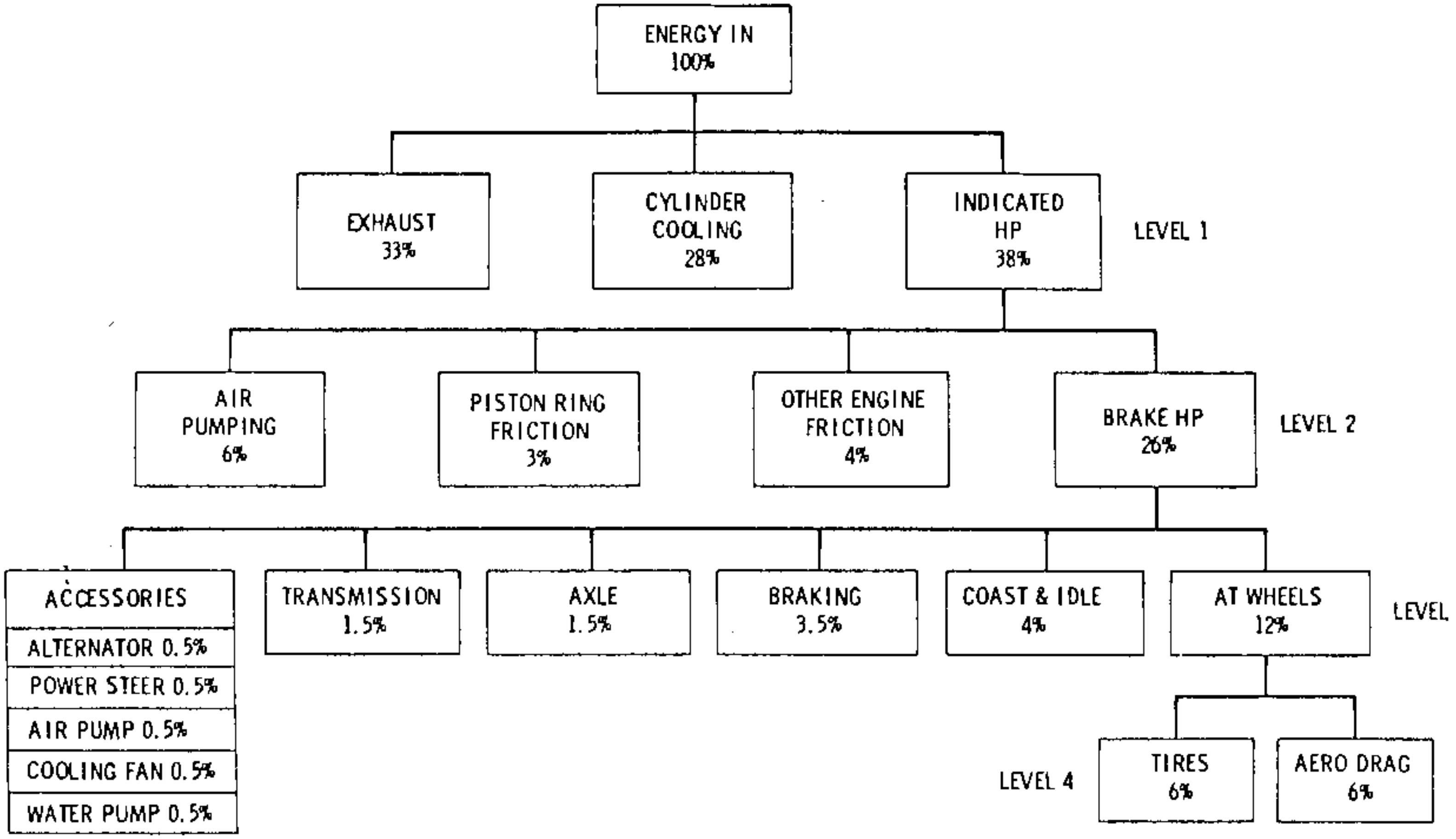
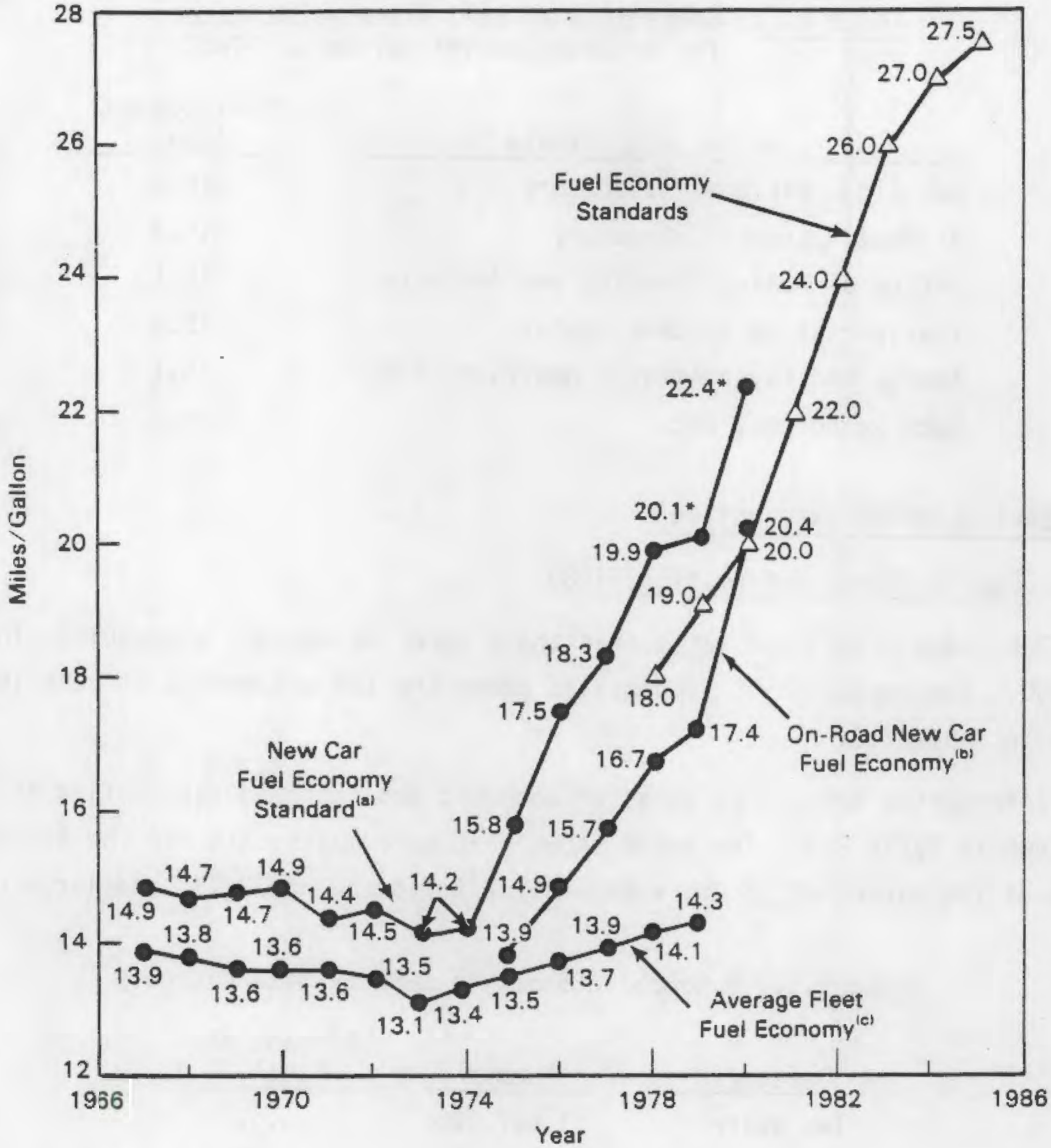


FIGURE 2.1. Energy Use in Passenger Car During EPA Cycle (Hopp 1981)

The improvement of engine efficiency is, however, only one facet that contributes to the efficiency of the delivered service, i.e., the automobile's fuel economy. Other mechanical elements that reduce the delivered efficiency are also shown in Figure 2.1. These include transmission loss; axle loss; and losses from accessories such as the alternator, power steering, air pump, cooling fan, water pump, air conditioning, and power brakes. Efficiency will be reduced further by rolling resistance and hysteresis losses in the tires and by aerodynamic drag. Developments in these nonengine areas, such as the use of steel-belted radial tires and automobile bodies with a lower coefficient of drag, can contribute significantly to increased efficiency. For example, using steel-belted radials can improve fuel economy by 5% to 15%, and reducing the aerodynamic drag on vehicles from 0.5 to 0.35 can improve fuel economy by 10% to 15% (AIP 1975). Reducing these nonengine loss mechanisms can thus be as significant as increasing the engine efficiency.

Perhaps the most influential contributor to fuel economy is vehicle weight. The relationship between fuel economy and vehicle weight is essentially linear, hence, improvements in fuel economy will be proportional to weight reduction. The relationship between vehicle weight and fuel economy is shown in Figure 2.2. Since 1975 the average automobile fleet fuel economy has been improving at 0.2 mpg annually (Oak Ridge 1981). The primary technical contribution to this trend has been the reduction in vehicle weight through improved design and lighter materials. Improvements in engine efficiency have yet to make a significant impact on fuel economy.

The average fuel economy for automobiles has been estimated by a number of sources, including Oak Ridge National Laboratory, Argonne National Laboratory, the DOE Office of Policy Planning and Analysis, the DOT Transportation Systems Center, Energy and Environmental Analysis, Inc., and Data Resources, Inc. These estimates have been compiled by Argonne and are presented in Table 2.1. The average among these estimates is 15.0 mpg in 1980. However, because the most detailed information was available from Oak Ridge, their figures will be used unless otherwise noted.



*Based on manufacturers' sales projection

[a]J.D. Murrell, J.A. Foster, and D.M. Bristor, Environmental Protection Agency, Passenger Car and Light Truck Fuel Economy Trends through 1980, SAE Paper 800853.

[b]Calculated 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.

[c]U.S. Department of Transportation, Federal Highway Administration, Highway Statistics, Washington, D.C., annual.

FIGURE 2.2. Automotive Fuel Economy Standards, 1967 to 1985 (Oak Ridge 1981)

TABLE 2.1. Comparison of Fuel Economy Estimates for Automobiles (Millar et al. 1982)

Source of Estimate	Fuel Economy (mpg)
Oak Ridge National Laboratory	14.0
Argonne National Laboratory	14.3
Office of Policy Planning and Analysis	15.1
Transportation Systems Center	15.9
Energy and Environmental Analysis, Inc.	15.1
Data Resources, Inc.	15.8

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 2.2.

Information describing sales of domestic and imported automobiles in 1980 is shown in Table 2.3. 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

TABLE 2.2. 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%
Midsize	25,471,000	24.4%
Large	34,582,000	33.1%

TABLE 2.3. 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.

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 cars, which had 20.0% and 19.9% of the market, respectively. A comparison of the market shift between 1978 and 1980 is provided in Table 2.4.

TABLE 2.4. 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
Midsize	31.6	37.5	33.7
Large	20.8	19.5	13.4

Information on the survival and scrappage rates of automobiles is illustrated in Figure 2.3 and Table 2.5. The survival probability curve for automobiles as a function of their age is shown in Figure 2.3. One can see from the figure that the "half-life" for automobiles is approximately 10 years. Points on the curve are tabulated in Table 2.5, which also presents information on scrappage rates, the number of vehicles in operation, and the percent of vehicle-miles traveled (by age group).

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 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. 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 2.6). The annual growth rates ranged from 1.2% to 1.9%.

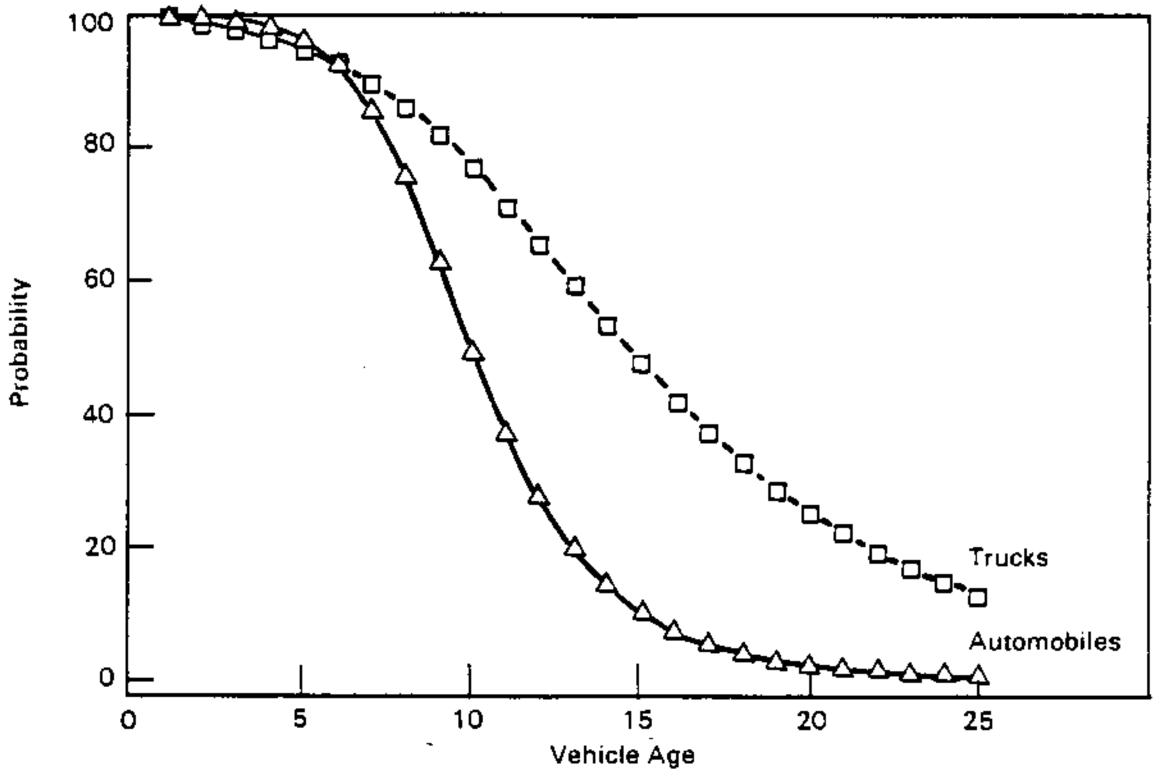


FIGURE 2.3. Survival Probability Curves for Automobiles and Light Trucks (Oak Ridge 1981)

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

Age (in years)	Number in Operation: Number in Thousands	Number in Operation: Percentage	Number in Operation: Cumulative Percentage	Survival Probability[a]	Scrappage Rate[b]	Percent of Total Vehicle Travel: Actual	Percent of Total Vehicle Travel: 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	21,451	20.6	100.0	--	--	15.0	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.

TABLE 2.6. Projections of Automobile Stock in 2000 (Knorr and Millar 1979, Millar et al. 1982)

Source of Projection	Estimated Stock ($x 10^6$)
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

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 referenced in Table 2.1.

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

TABLE 2.7. Summary of Projected Automobile Ownership, Use, and Energy Demand

	1980	2000 Case A	2000 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).

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 that 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.

TABLE 2.8. R&D Applications Summary - Automobiles

Data Item/ Fuel Type	UPHS Average Efficiency 1980	# Unit Process Hardware Systems 1980	# Unit Process Hardware Systems 2000	Fuel Consumption Demand (Btu) 1980	Fuel Consumption Demand (Btu) 2000	Product or Service Activity Level (ton-miles) 1980	Product or Service Activity Level (ton-miles) 2000
Gasoline	26%	104,564,000	110,000,000	$9,740 \times 10^{12}$	$7,050 \times 10^{12}$	$2,060 \times 10^{9}$	$1,910 \times 10^{9}$

TABLE 2.9. Market Data Summary - Automobiles

Data Item/ Fuel Type	Total # Unit Process Hardware Systems 1980	Total Projected # Unit Process Hardware Systems 2000	# UPHS Due to Industry Capacity Expansion (Increased Service Demand) 2000	# UPHS Due to Replacement of Obsolete Units 2000	# UPHS from 1980 Remaining in Service 2000
Gasoline	104,564,000	110,000,000	5,436,000	101,427,000	3,136,920

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)

Size Class	Number	Weight Class Gross Vehicle Weight (lb)
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. The fuel consumption, capital stock and activity data are summarized at the end of this section in Tables 3.6 and 3.7.

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)

Source of Estimate	Fuel Economy (mpg)
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)

Source of Projection	Stock (10^6) 1980	Stock (10^6) 2000	Avg. Annual % Change
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 2.3, 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

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)

Source of Projection	Gasoline Energy Use (quads) 1980	2000	Avg. Annual % Change
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 x 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 x 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	2.2 %
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 x 10^9 ton-miles for gasoline vehicles and 2.6 x 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)

Use Sector	Projected Light Trucks 10^6 Trucks 1975	Projected Light Trucks 10^6 Trucks 2000	Percent Change
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	1.4	1.8	29
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 x 10^9 ton-miles for gasoline vehicles and 3.62 x 10^9 ton-miles for light trucks fueled by LPG.

TABLE 3.6. R&D Applications Summary - Light Trucks

Data Item/ Fuel Type	UPHS Average Efficiency 1980	# Unit Process Hardware Systems 1980	# Unit Process Hardware Systems 2000	Fuel Consumption Demand (Btu) 1980	Fuel Consumption Demand (Btu) 2000	Product or Service Activity Level (ton-miles) 1980	Product or Service Activity Level (ton-miles) 2000
Gasoline	26%	28,900,000	33,300,000	2.71 x 10^{12}	2.82 x 10^{12}	877,000,000	1,063,000,000
LPG	26%	87,000	108,000	7.25 x 10^{12}	7.55 x 10^{12}	2,600,000	3,260,000

TABLE 3.7. Market Data Summary - Light Trucks

Data Item/ Fuel Type	Total # Unit Process Hardware Systems 1980	Total Projected # Unit Process Hardware Systems 2000	# UPHS Due to Industry Capacity Expansion (Increased Service Demand) 2000	# UPHS Due to Replacement of Obsolete Units 2000	# UPHS from 1980 Remaining in Service 2000
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

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. Fuel consumption, capital stock, and activity data are summarized at the end of this section in Tables 4.12 and 4.13.

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

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

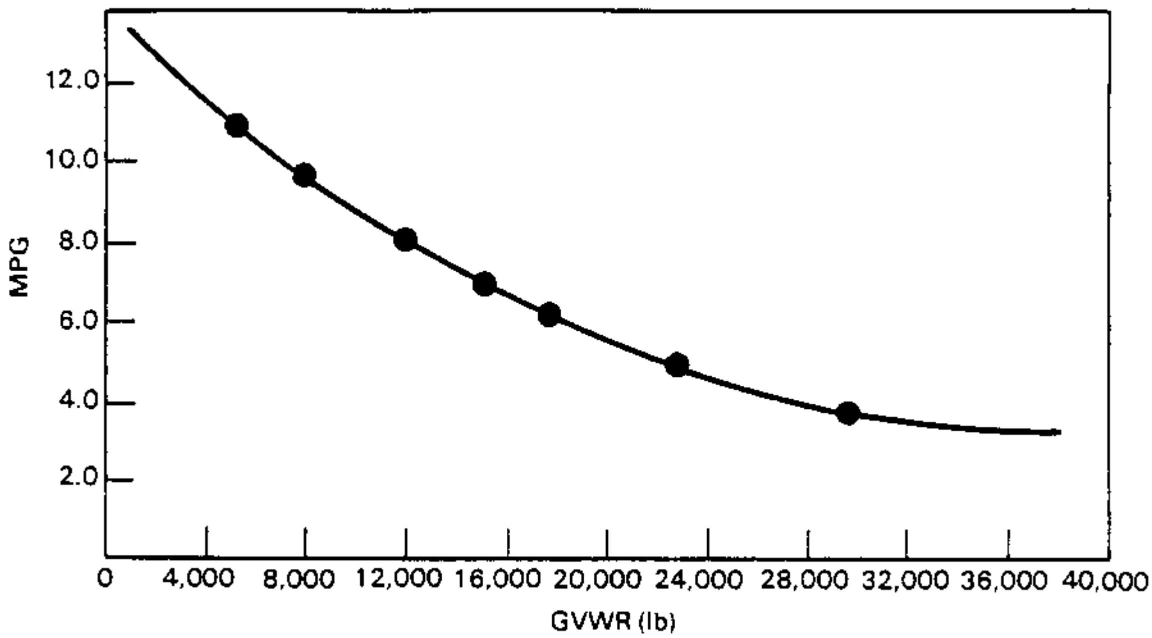


FIGURE 4.1. Fuel Consumption Rates for Local Gasoline-Powered Vehicles by Gross Vehicle Weight Rating (JFA 1976)

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

Source of Projection	Stock (10^6) 1980	Stock (10^6) 2000	Avg. Annual % Change
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)

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

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

Trucks	Domestic Sales	Imported Sales[a]
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

Trucks	Sales
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 x 10^{12} Btu of gasoline and 4.0 x 10^{12} Btu of LPG were

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

Source of Projection	Energy Use (quads) 1980	Energy Use (quads) 2000	Avg. Annual % Change
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 x 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 x 10^{12} Btu for gasoline consumption and 4.0 x 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

Size Category	Energy Consumption (Gasoline & LPG, x 10^{12} Btu)	Percent of Total
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 x 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 x 10^{12} Btu of gasoline and 4.4 x 10^{12} Btu of LPG used. This study will estimate consumption at 600 x 10^{12} Btu of gasoline and 4.4 x 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

Size Category	Energy Consumption (Gasoline & LPG, x 10^{12} Btu)	Percent of Total
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

TABLE 4.9. Activity for Gasoline-Fueled Trucks in 1980

	Truck Size Class		
Average Vehicle Miles	Medium	Light-heavy	Heavy-heavy
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

service of 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] Light	Medium	Light-heavy	Heavy-heavy[c]	Total
			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 transportation	55.2	5.6	0.1	(d)	31.3
Other	2.2	8.4	8.6	8.7	5.1
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 transportation	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

Average Vehicle-Miles	Truck Size Class Medium	 Light-heavy	 Heavy-heavy
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

TABLE 4.12. R&D Applications Summary - Medium and Heavy Trucks

Data Item/ Fuel Type	UPHS Average Efficiency 1980	# Unit Process Hardware Systems 1980	# Unit Process Hardware Systems 2000	Fuel Consumption Demand (Btu) 1980	Fuel Consumption Demand (Btu) 2000	Product or Service Activity Level (ton-miles) 1980	Product or Service Activity Level (ton-miles) 2000
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 4.13. Market Data Summary - Medium and Heavy Trucks

Data Item/ Fuel Type	Total # Unit Process Hardware Systems 1980	Total Projected # Unit Process Hardware Systems 2000	# UPHS Due to Industry Capacity Expansion (Increased Service Demand) 2000	# UPHS Due to Replacement of Obsolete Units 2000	# UPHS from 1980 Remaining in Service 2000
Gasoline	3,575,000	3,293,000	--	2,399,000	894,000
LPG	10,760	9,930	--	7,240	2,690

5.0 MARINE

Marine transportation is typically divided into two end-use categories: freight vehicles and recreational vehicles. Because of the large power requirements of freight vehicles, their engines are generally large diesels or turbines using distillate or residual fuel oil. Virtually no freight vehicles use gasoline as a fuel. The recreational boating subsector dominates the use of gasoline in marine engines.

There were 1.46 quads of energy consumed in marine engines in 1977; of that amount, 0.189 quads was gasoline. Approximately 95% of the energy used in recreational boats is in the form of gasoline. Developments in Otto cycle engines can thus impact this element of the marine sector.

Two types of engines are used in all gasoline-consuming recreational boats: outboard and inboard. Outboard engines, which compose 80% of the engines used, are typically two-stroke Otto cycle engines. Inboard engines, which compose the remaining 20%, are typically four-stroke Otto cycle engines and are actually converted automobile engines.

The primary source of information regarding recreational boat use and energy consumption is the study Energy Conservation Potential for Recreational Boating Activity, performed by Jack Faucett Associates (JFA) (1979). The fuel consumption, capital stock, and activity data are summarized at the end of this chapter in Tables 5.2 and 5.3.

5.1 EFFICIENCY ESTIMATE

There are two basic types of Otto cycle engines used in recreational boating: the two-stroke outboard engine and the four-stroke inboard engine.

The inboard engines are essentially converted automobile engines, hence much of the discussion regarding automobile engine efficiencies in Section 2.1 applies. The typical maximum delivered or brake thermal efficiency of the four-stroke inboard engine is 26%.

The two-stroke design is used in outboard engines because of its specific power and its cost advantages over the four-stroke engine. The two-stroke engine has twice as many power strokes per cycle as does the four-stroke engine. As a result, the power output per unit piston displacement is 50% to 80% greater than its four-stroke counterpart. The design of the two-stroke engine is also simpler, using ports in the cylinder wall for intake and exhaust rather than valves. Because of its less expensive design and higher specific power output, the two-stroke engine is favored in outboard engines.

However, this engine is less thermally efficient than the four-stroke design. It is less efficient because the two-stroke design requires that the combusted charge be exhausted simultaneously with the induction of a fresh fuel-air mixture. The process of exhausting the combusted mixture and inducting a fresh fuel-air charge is known as scavenging.

In the ideal scavenging process, the fresh fuel-air mixture would push out the residual gases before exchanging any heat with those gases. The ideal process thus fills the cylinder at bottom dead center with fresh mixture that is at the inlet temperature and at exhaust system pressure. To achieve this pressure equalization by bottom dead center and to avoid excessive blowback of the unburned gases into the inlet system, the exhaust ports must open early. This early opening of the exhaust ports decreases the amount of work performed during each cycle and thus decreases the indicated efficiency of the engine.

Other factors that reduce the efficiency of the engine include the mixing of the fresh mixture with the residual gases and the consequent heat exchange, as well as the loss of some of the fresh mixture during the exhaust process. Taylor (1966) estimates that, as a result of these effects, the indicated efficiency of the two-stroke engine is typically 85% to 95% that of a comparable four-stroke engine.

Between the indicated efficiency and the brake efficiency there are additional losses due to friction, throttling, and compression of the fresh fuel-air mixture to facilitate scavenging. In small engines, such as outboard motors, this compression occurs in the crankcase and reduces the efficiency by an additional 7% to 12% (Obert 1973). Thus, if we assert that a nominal value for the brake efficiency of the four-stroke engine is 25%, the efficiency of a comparable two-stroke engine would be approximately 19%.

In any complete discussion of energy conservation potential, it should be remembered that the engine efficiency is but one element. Other factors that affect the efficiency with which the boat is propelled include propeller design (which converts engine power to thrust), the hull design, the weight of the boat, and the use of trim tabs.

5.2 CAPITAL STOCK INFORMATION

5.2.1 Capital Stock Information, 1980

Table 5.1 presents capital stock data for the various categories of recreational boats; 80% of the engines used are outboard engines with an average rating of approximately 45 hp. The remaining 20% of the engines are inboards with horsepower ratings that range between 100 hp and 300 hp. The distribution of inboard versus outboard engines at various horsepower ratings is shown in Figure 5.1.

JFA (1979) estimated that there were 8.4 million recreational boats in 1977. Estimates for the stock in 1980 can be made by drawing upon other information provided by JFA. JFA noted that the rate of new boat sales had been fairly constant over the 15 years previous to 1977, in the range of 5 to 6 boats sold per thousand families. Assuming that ownership increased at this rate, the fleet size for 1980 can be estimated at 9.3 million boats. Outboard motors are used in 7.44 million boats, and inboard motors in the remaining 1.86 million.

One important caveat is that information regarding the turnover of capital stock is not available from current data sources (JFA 1979). It is therefore difficult to double-check the accuracy of the various data sources, or to project fleet growth with confidence.

5.2.2 Capital Stock Information, 2000

In the absence of stock turnover information, projections to the year 2000 are very tenuous. However, using information that appears consistent with past

TABLE 5.1. Estimates of 1977 Fleet Composition and Fuel Consumption (JFA 1979)

Type of Boat	Boats with Motors (thousands)	Annual Fuel Consumed per Boat (gallons)	Annual Fuel Consumed Amount (thousands of gallons)	Percent of Total
Rowboat	886	42	37,147	2.5
Skiff	250	105	26,321	1.8
Dinghy	74	40	2,970	0.2
Johnboat	955	89	84,897	5.7
Other Open Lightweight	1,027	140	143,785	9.6
Sailboat	182	41	7,444	0.5
Canoe	101	18	1,780	0.1
Kayak	5	3	13	(a)
Bowrider Runabout	1,623	172	278,959	18.6
Non-Bowrider Runabout	1,428	160	229,026	15.3
Cabin Cruiser	508	559	283,852	18.9
Houseboat	45	375	16,861	1.1
Inflatable Boat	5	4	21	(a)
Inflatable Raft	1	10	10	(a)
Non-inflatable Raft	12	135	1,618	0.1
Pontoon Boat	121	90	10,915	0.7
Thrill Craft	151	253	38,130	2.5
Other	1,026	328	336,251	22.4
Total	8,400	179	1,500,000	100.0

(a) Less than 0.05%.

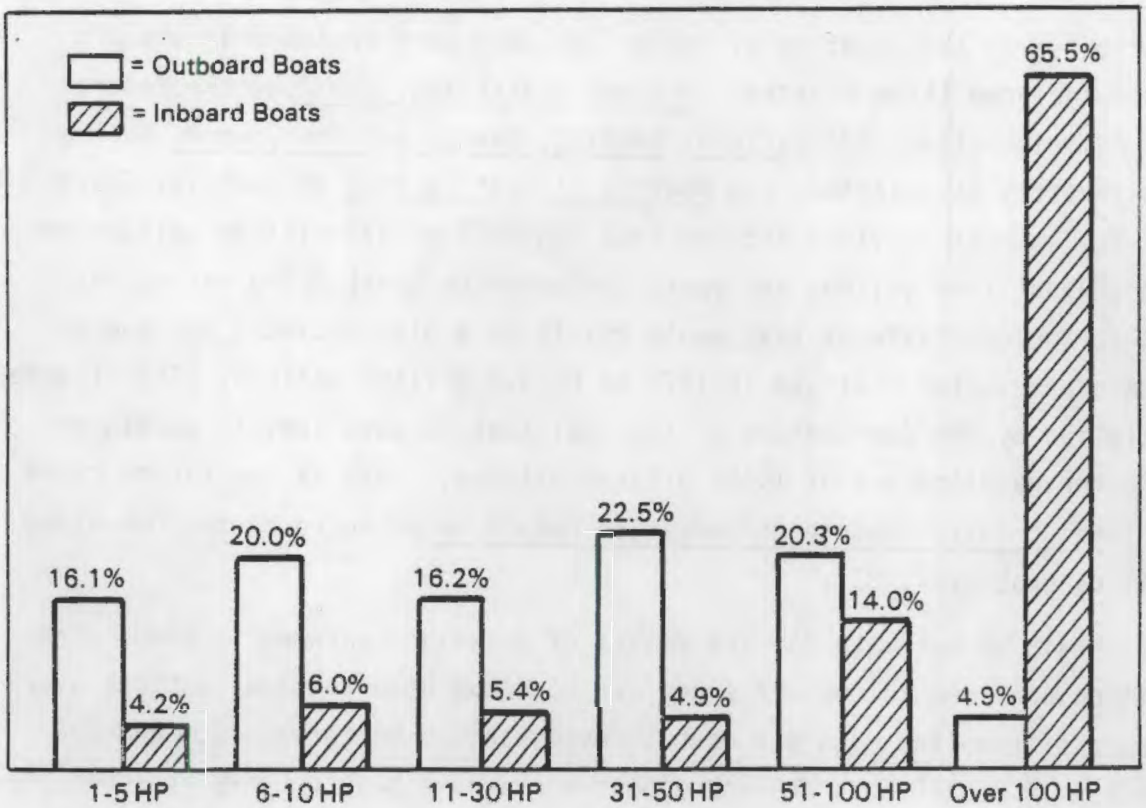


FIGURE 5.1. 1973 Horsepower Distribution of Inboard and Outboard Boats (JFA 1979)

trends (e.g., assuming the growth rate in ownership per family remains constant), JFA estimates that the recreational boating fleet would grow at an annual rate of 2.4% and that energy use would grow at a rate of 2.2% per year between 1980 and 2000. Thus, JFA estimates that the recreational boat fleet in the year 2000 will consist of 15 million vehicles.

JFA has noted a recent trend toward inboard motors and larger outboard motors. Assuming that the ratio of inboard to outboard motor stock shifts from 1:5 in 1980 to 1:4 in 2000, there will be 3.75 million inboard motors and 11.25 million outboard motors in 2000.

5.3 FUEL CONSUMPTION DEMAND

5.3.1 Fuel Consumption Demand, 1980

Approximately 95% of the energy used in recreational boating is in the form of gasoline. Small engines using electric energy accounted for over 3% of the energy used, and use of diesel fuel accounted for the remainder.

Estimates of the quantity of energy consumed were reviewed in the JFA study and included three sources: Highway Statistics: 1977 by the Federal Highway Administration, Recreational Boating, Energy and the Economy by the Boating Industry Association, and Boating Statistics 1978 by the U.S. Coast Guard. The sources provided figures that ranged from 774 million gallons per year to 3071 million gallons per year. Because the Coast Guard survey was thought to include features that would result in a high estimate for energy use, JFA approximated fuel use in 1978 to be 1.5 billion gallons. This figure is multiplied by 95% (percentage of the fuel that is gasoline) to obtain an estimate for gasoline use of 1.425 billion gallons. This is the figure cited in the Transportation Energy Conservation Data Book produced by the Oak Ridge National Laboratory (1981).

To obtain an estimate for the amount of gasoline consumed in 1980, other information provided in the JFA study can be drawn upon to show that the average amount of gasoline used per boat is estimated to be between 100 and 250 gallons/year. Recall that JFA found boat sales have been roughly constant over the past 15 years at between 5 and 6 boats per thousand families.

Assuming that the growth in energy use parallels the growth in the number of sales, that the ownership ratio remains the same (an increase of 5 boats per thousand families), and that the average gasoline use is 200 gallons/year, the gasoline consumed in 1980 can be estimated at 1.77 billion gallons of gasoline or 220×10^{12} Btu. This is roughly in agreement with changes predicted by ORNL using the same JFA study as a base source.

Though inboard engines compose only 20% of the engines used, they account for 40% of the energy consumed, or 88×10^{12} Btu. Inboard engines are notably larger than outboard, hence they consume a disproportionate percentage of fuel. The average outboard engine is rated at approximately 45 hp, whereas the average inboard engine is over 100 hp. Outboard engines account for the remaining 132×10^{12} Btu. A list of the different categories of recreational boats and the energy consumed by each is shown in Table 5.1.

5.3.2 Fuel Consumption Demand, 2000

Using the projection method described in Section 5.2.2 (capital stock changes), it is estimated that the fleet of 15 million boats will consume 2.7 billion gallons of gasoline (338×10^{12} Btu). Again, assuming that inboard engines grow to 25% of the capital stock, it is estimated that half of this gasoline will be consumed by inboard engines and half by outboard engines.

5.4 SERVICE ACTIVITY LEVEL

Because information describing annual miles traveled or typical load factors for the large variety of recreational boats is lacking, the activity of recreational boating could not be determined. Figure 5.2 gives a breakout of the end-use services provided in recreational boating.

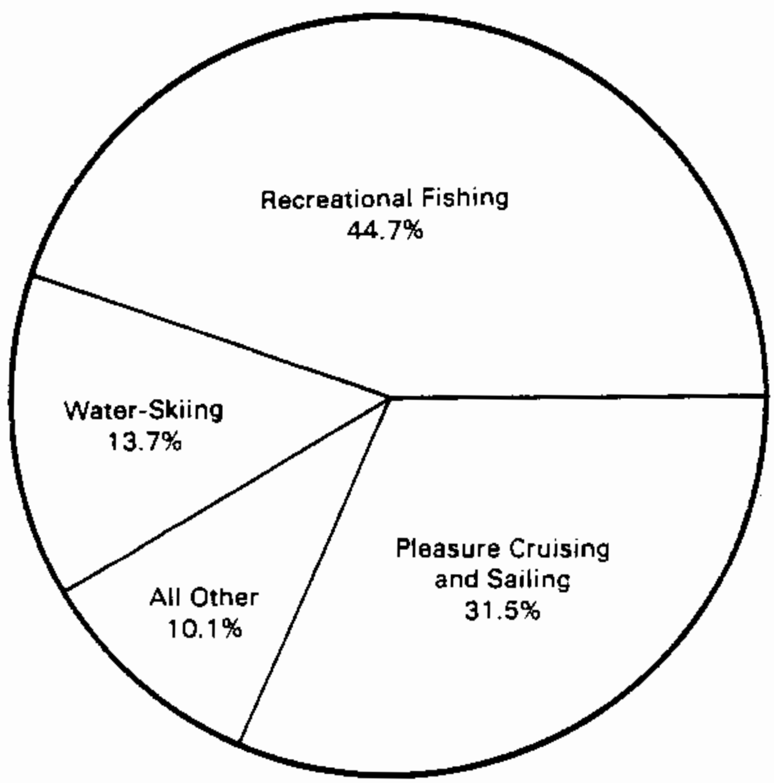


FIGURE 5.2. Time Spent in Boating Activities (JFA 1979)

TABLE 5.2. R&D Applications Summary - Marine

Data Item/ Fuel Type	UPHS Average Efficiency 1980	# Unit Process Hardware Systems 1980	# Unit Process Hardware Systems 2000	Fuel Consumption Demand (Btu) 1980	Fuel Consumption Demand (Btu) 2000	Product or Service Activity Level (ton-miles) 1980	Product or Service Activity Level (ton-miles) 2000
Gasoline-outboard	19%	7,440,000	11,250,000	132×10^{12}	169×10^{12}	--	--
Gasoline-inboard	26%	1,860,000	3,750,000	88×10^{12}	169×10^{12}	--	--

TABLE 5.3. Market Data Summary - Marine

Data Item/ Fuel Type	Total # Unit Process Hardware Systems 1980	Total Projected # Unit Process Hardware Systems 2000	# UPHS Due to Industry Capacity Expansion (Increased Service Demand) 2000	# UPHS Due to Replacement of Obsolete Units 2000	# UPHS from 1980 Remaining in Service 2000
Gasoline-outboard	7,440,000	11,250,000	3.81×10^6	--	--
Gasoline-inboard	1,860,000	3,750,000	1.89×10^6	--	--

6.0 RECREATIONAL VEHICLES

Recreational vehicles include travel trailers, camping trailers, truck campers, and motorhomes. These vehicles typically have the same load, engine, and energy-use characteristics as light trucks. Unfortunately, detailed descriptions of vehicle use in this sector are not readily available.

The source used for this discussion is the Oak Ridge transportation book (1981). The fuel consumption, capital stock, and activity data are summarized at the end of this section in Tables 6.2 and 6.3.

6.1 EFFICIENCY ESTIMATE

Recreational vehicles typically use four-stroke Otto cycle engines with efficiency characteristics similar to the automobile engine. For a discussion of these efficiency characteristics see Section 2.1. The estimated fuel economy for recreational vehicles is approximately 10 mpg.

6.2 CAPITAL STOCK INFORMATION

There were approximately 6 million recreational vehicles in operation in 1980. Oak Ridge estimated that 308,000 vehicles were sold during the previous year, 1979. The sales information for various categories of recreational vehicles is summarized in Table 6.1.

Unfortunately, projections of the capital stock to the year 2000 were not available. Such a projection would be difficult to estimate because of consumer response to higher energy prices and because survival curves for these vehicles are not available.

6.3 FUEL CONSUMPTION DEMAND

During 1980, recreational vehicles consumed 702.4 million gallons of gasoline (87.8×10^{12} Btu), or 0.7% of the gasoline used in transportation.

TABLE 6.1. Summary Statistics for Recreational Vehicles

	Shipments, 1979 (thousands)	In Operation, 1979 (thousands)	Average Load Factor During An Outing, 1973	Estimated Fuel Efficiency		Average Annual Vehicle Travel, 1974	
				mpg	liters/ 100 km	miles	km
Travel Trailers	90.2	2,150					
Conventional	74.7	2,040	3.7			2,400	3,862
Fifth Wheel	15.5	110	3.2			3,150	5,069
Camping Trailers	31.1	1,199	4.8			2,150	3,460
Truck Campers	13.8	1,370	3.8			4,650	7,483
Motorhomes	172.6	781					
Type A--conventional	21.5	424	4.3	8.3	28.3	6,900	11,105
Type B--van conversions	111.9	176	3.4	12.5	18.8	11,500	18,506
Type C--mini motorhomes	39.2	181	3.7	9.5	24.8	7,600	12,230
Total RVs	307.7	5,500		9.8	24.0		

6.4 SERVICE ACTIVITY LEVEL

Information summarizing the average load factor and average annual vehicle-miles traveled by the various categories of recreational vehicles is shown in Table 6.1. The load factor in 1973 can be seen to vary from 3.2 for fifth-wheel travel trailers to 4.8 for camping trailers. The average annual miles traveled in 1974 is seen to vary from 3,460 for camping trailers to 18,506 for motorhomes (van conversions).

Assuming that the average vehicle travel in 1980 was similar to that shown for 1974 in Table 6.1, the total vehicle-miles traveled in 1980 is approximately 2.30×10^{10} miles. Further assuming an average load factor of 4 and an average unloaded vehicle weight of 5,000 lb, the number of ton-miles is estimated to be 64.4×10^9 ton-miles.

TABLE 6.2. R&D Applications Summary - Recreational Vehicles

Data Item/ Fuel Type	UPHS Average Efficiency 1980	# Unit Process Hardware Systems 1980	# Unit Process Hardware Systems 2000	Fuel Consumption Demand (Btu) 1980	Fuel Consumption Demand (Btu) 2000	Product or Service Activity Level (ton-miles) 1980	Product or Service Activity Level (ton-miles) 2000
Gasoline	26%	6,000,000	--	87.8×10^{12}	--	64.4×10^{9}	--

TABLE 6.3. Market Data Summary - Recreational Vehicles

Data Item/ Fuel Type	Total # Unit Process Hardware Systems 1980	Total Projected # Unit Process Hardware Systems 2000	# UPHS Due to Industry Capacity Expansion (Increased Service Demand) 2000	# UPHS Due to Replacement of Obsolete Units 2000	# UPHS from 1980 Remaining in Service 2000
Gasoline	6,000,000	--	--	--	--

7.0 MOTORCYCLES

The primary source of information describing motorcycle use was, again, the Oak Ridge transportation book (1981). In this data book, motorcycles are estimated to be the seventh largest gasoline-consuming mode in transportation, accounting for 0.5% of the gasoline used in transportation. The fuel consumption, capital stock, and activity data are summarized at the end of this section in Tables 7.1 and 7.2.

7.1 EFFICIENCY ESTIMATE

Prior to the mid-1970s, two-stroke engines were used in most motorbikes because their power-to-weight ratio is greater than that of four-stroke engines. With the tightening of emission standards, use of the four-stroke engine increased significantly. By 1980, all street bikes and most other motorcycles used four-stroke engines. The efficiency characteristics of these four-stroke engines are similar to those described in Section 2.1.

7.2 CAPITAL STOCK INFORMATION

The most recent stock and activity data are presented in the Oak Ridge transportation book and are for the year 1979. These data indicate that there were 7,035,500 vehicles in operation.

7.3 FUEL CONSUMPTION DEMAND

Data from Oak Ridge (1981) indicate that motorcycles and mopeds consumed 527 million gallons of gasoline (65.9×10^{12} Btu) in 1980, thus accounting for 0.5% of the gasoline used in transportation.

7.4 SERVICE ACTIVITY LEVEL

Oak Ridge data for 1979 indicate that motorcycles and mopeds traveled a total of 24,607 million miles, while carrying passengers a total of 27,068 million miles. The load factor (ratio of passenger-miles traveled to vehicle-miles traveled) was approximately 1.1. Assuming an average vehicle weight of

450 lb carrying an average load of 165 lb, the annual load per vehicle was 1080 ton-miles. This translates to a total of 7.60×10^9 annual ton-miles for all motorcycles.

TABLE 7.1. R&D Applications Summary - Motorcycles

Data Item/ Fuel Type	UPHS Average Efficiency 1980	# Unit Process Hardware Systems 1980	# Unit Process Hardware Systems 2000	Fuel Consumption Demand (Btu) 1980	Fuel Consumption Demand (Btu) 2000	Product or Service Activity Level (ton-miles) 1980	Product or Service Activity Level (ton-miles) 2000
Gasoline	26%	7,035,500 (1979)	--	65.9×10^{12} (1981)	--	7.60×10^9	--

TABLE 7.2. Market Data Summary - Motorcycles

Data Item/ Fuel Type	Total # Unit Process Hardware Systems 1980	Total Projected # Unit Process Hardware Systems 2000	# UPHS Due to Industry Capacity Expansion (Increased Service Demand) 2000	# UPHS Due to Replacement of Obsolete Units 2000	# UPHS from 1980 Remaining in Service 2000
Gasoline	7,035,500 (1979)	--	--	--	--

8.0 BUSES

The bus sector of transportation consists of three primary categories: intercity buses, local buses, and school buses. Intercity buses and local buses tend to be large vehicles that use diesel engines almost exclusively. School buses are significantly different; they are essentially bus cabs mounted on truck chassis. In contrast to the intercity and local buses, all of the fuel consumed by school buses is gasoline. Because this accounts for 97% of the gasoline used by buses, the discussion will center around the characteristics and energy use of school buses. Fuel consumption, capital stock, and activity data are summarized at the end of this section in Tables 8.1 and 8.2.

8.1 EFFICIENCY ESTIMATE

Buses use four-stroke Otto cycle engines with efficiency characteristics similar to those of the automobile engine. See Section 2.1 for a discussion of these characteristics. School buses averaged 4.5 mpg of gasoline in 1980, with the mini-buses averaging 10-12 mpg.[a]

8.2 CAPITAL STOCK INFORMATION

8.2.1 Capital Stock Information, 1980

It is estimated that approximately 400,000 school buses were in use in 1980.[a] Of these, approximately 390,000 used Otto cycle engines, and of these, 25,000 were small buses that averaged 10-12 mpg.[a] By comparison, Oak Ridge (1981) estimated that 418,000 school buses were in use in 1979, and Argonne (Millar et al. 1982) estimated that 405,900 school buses with Otto cycle engines were in use in 1980.

8.2.2 Capital Stock Information, 2000

Argonne projects that the overall stock of school buses will increase to the year 2000. However, this increase will be satisfied through the growing

(a) Conversation with B. Reynolds, National School Transportation Board, 1982.

use of medium-sized diesel engines, which are more efficient than Otto engines. The number of Otto engines is estimated to decrease at an average annual rate of 1.2%. Applying this projection to the Otto engine stock of 390,000 vehicles in 1980 yields an estimated stock of 306,000 in 2000.

8.3 FUEL CONSUMPTION DEMAND

8.3.1 Fuel Consumption Demand, 1980

Oak Ridge estimates that buses consumed 127 x 10^{12} Btu of energy in 1980, accounting for 0.7% of the energy used in transportation. Diesel fuel accounted for 62% of this energy use and gasoline for the remaining 38%, or 50 x 10^{12} Btu (400 million gallons of gasoline). This agrees with the values determined by Argonne (Knorr and Millar 1979). Gasoline consumed by buses represented 0.4% of the gasoline used in transportation.

8.3.2 Fuel Consumption Demand, 2000

The shift to diesel engines is anticipated to reduce the demand for Otto engine school buses in 2000. Fewer Otto engine buses will be operating and they will be driving fewer miles. Argonne (Millar et al. 1982) projects that this will result in an average annual decrease in gasoline demand of -2%. The resultant gasoline demand in 2000 is 33 x 10^{12} Btu.

8.4 SERVICE ACTIVITY LEVEL

8.4.1 Service Activity Level, 1980

Oak Ridge (1981) estimates that school buses carried an estimated 7,850 million passengers a total of 74,500 million passenger-miles in 1979. The total number of vehicle-miles traveled was 2,980 million miles.

Assuming an average bus weight of 14,000 lb[(a)] and an average passenger load of 3,000 lb, the average annual load per vehicle was 63,000 ton-miles. This translates to 24.7 x 10^9 ton-miles for all gasoline-fueled school buses.

(a) Conversation with B. Reynolds, 1982.

8.4.2 Service Activity Level, 2000

Argonne (Millar et al. 1982) projects that the miles traveled by gasoline-fueled school buses will decrease at an average annual rate of 0.8% between 1980 and 2000. Assuming that the average bus load remains constant, the average annual load per vehicle will decrease to 53,650 ton-miles. This translates to a total of 16.4×10^9 ton-miles for all gasoline-fueled school buses.

TABLE 8.1. R&D Applications Summary - Buses

Data Item/ Fuel Type	UPHS Average Efficiency 1980	# Unit Process Hardware Systems 1980	# Unit Process Hardware Systems 2000	Fuel Consumption Demand (Btu) 1980	Fuel Consumption Demand (Btu) 2000	Product or Service Activity Level (ton-miles) 1980	Product or Service Activity Level (ton-miles) 2000
Gasoline	26%	390,000	306,000	50×10^{12}	33×10^{12}	24.7×10^9	16.4×10^9

TABLE 8.2. Market Data Summary - Buses

Data Item/ Fuel Type	Total # Unit Process Hardware Systems 1980	Total Projected # Unit Process Hardware Systems 2000	# UPHS Due to Industry Capacity Expansion (Increased Service Demand) 2000	# UPHS Due to Replacement of Obsolete Units 2000	# UPHS from 1980 Remaining in Service 2000
Gasoline	390,000	306,000	--	208,500	97,500

9.0 AIRCRAFT

Four categories of aircraft compose this subsector of transportation: 1) jets, 2) propeller aircraft, which includes both turboprop and piston-driven engines, 3) rotorcraft, and 4) others. Of the 201,324 aircraft in operation in 1978, Oak Ridge (1981) estimates that 2.3% were jets, 93.0% were propeller aircraft, 2.6% were rotorcraft, and 2.0% were in the fourth (other) category.

The transportation services offered by aircraft are divided between two classes of operation: air carrier and general aviation. Although only half of the jets and less than 0.2% of the propeller aircraft are classified as air carriers, this category of service accounted for 94% of the passenger-miles traveled, 33% of the vehicle-miles traveled, and 91.6% of the energy used by aircraft in 1979.

There are two principal types of fuel used by aircraft: jet fuel and aviation gasoline. Only aviation gasoline is used in Otto cycle engines.

The primary users of Otto cycle engines are the piston aircraft and the rotorcraft. Over 99.9% of the piston aircraft and essentially 100% of the rotorcraft are used in general aviation. These two categories compose 95% of the aircraft used in general aviation.

The information appearing in this discussion was taken from the Oak Ridge Transportation Energy Conservation Data Book. The primary source of the Oak Ridge data was the FAA Statistical Handbook, which is revised annually. Fuel consumption, capital stock, and activity data are summarized at the end of this section in Tables 9.2 and 9.3.

9.1 EFFICIENCY ESTIMATE

The Otto cycle engines used are typically four-stroke engines with compression ratios similar to those of automobile engines (8:1 to 8.5:1). Their overall delivered efficiency would be expected to be approximately the same. However, conversations with Avco-Lycoming[a] indicate slightly higher

(a) Conversation with Mr. Gerber, Avco-Lycoming, 1982.

efficiencies are being achieved. Avco-Lycoming performance data show that when their engine is operating at best economy, the efficiency is approximately 33%. When the engine is operating for best power, the efficiency is 27%. Both values are higher than the 20% to 26% typical of automobile engines. The reasons are not clear, but this may be due in part to the more constant load experienced by aircraft engines. A discussion of typical loss mechanisms is included in Section 2.1.

9.2 CAPITAL STOCK INFORMATION

Data for 1978 (Oak Ridge 1981) indicate that there were 183,891 piston aircraft and 5,318 rotorcraft in use. Only 68 of the piston aircraft and three of the rotorcraft were used by air carriers; the remainder were categorized under general aviation.

9.3 FUEL CONSUMPTION OEMAND

In 1980, Otto cycle civilian aircraft consumed approximately 65×10^{12} Btu of aviation gasoline (537 million gallons). This accounted for D.4% of the gasoline used in transportation. In 1979, military aircraft consumed 3.8×10^{12} Btu (31 million gallons) of the aviation gasoline.

9.4 SERVICE ACTIVITY LEVEL

Most of the hours logged by Otto cycle aircraft were under general aviation. General aviation accounted for 99.5% of the 34.2 million hours of flight time logged by piston engines and for 99.8% of the 2.23 million hours logged by rotorcraft. A breakdown of the uses of piston aircraft and rotorcraft in general aviation is shown in Table 9.1.

Because Otto cycle aircraft dominate general aviation in both the total number of aircraft and in flight time, the characteristics of general aviation will be used to compute the energy intensity of the service. The weight of aircraft in general aviation is highly variable, thus the energy intensity will be given in terms of energy per vehicle-mile traveled (VMT) and energy per passenger-mile traveled (PMT). These figures for 1979 are 23,100 Btu/VMT and 9,D20 Btu/PMT (Oak Ridge 1981).

TABLE 9.1. Distribution of General Aviation Piston Aircraft and Rotorcraft by Primary Use and Owner, 1978 (Oak Ridge 1981)

Activity	Percent of Total Number	
	Piston Aircraft	Rotorcraft
Executive	4.3	9.2
Business	22.6	12.1
Personal	50.5	9.6
Aerial Application	3.6	14.8
Instructional	7.6	5.1
Air Taxi	3.3	22.9
Industrial	0.9	7.6
Rental	4.2	2.4
Other	2.9	16.3

TABLE 9.2. R&D Applications Summary - Aircraft

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
Aviation Gasoline	30%	189,210	--	68.8×10^{12}	--	--	--

TABLE 9.3. Market Data Summary - Aircraft

Data Item/ Fuel Type	Total # Unit Process Hardware Systems	Total Projected # Unit Process Hardware Systems	# UPHS Due to Industry Capacity Expansion (Increased Service Demand)	# UPHS Due to Replacement of Obsolete Units	# UPHS from 1980 Remaining in Service
	1980	2000	2000	2000	2000
Aviation Gasoline	189,210	--	--	--	--

10.0 SNOWMOBILES

The primary sources of data that describe the use of snowmobiles are the Snowmobiling Fact Book distributed by the International Snowmobiling Industry Association (ISIA) (1982) and the Transportation Energy Conservation Data Book published by Oak Ridge. Oak Ridge data were, however, based largely upon information provided in the Snowmobiling Fact Book. The fuel consumption, capital stock, and activity data are summarized at the end of this chapter in Tables 10.1 and 10.2.

10.1 EFFICIENCY ESTIMATE

Snowmobiles typically use two-stroke Otto cycle engines. For a discussion of the efficiency characteristics see Section 2.1.

10.2 CAPITAL STOCK INFORMATION

The most recent estimate by Oak Ridge (1981) is that there were 1,880,000 snowmobiles in use in 1978.

10.3 FUEL CONSUMPTION DEMAND

The primary fuel used by snowmobiles is gasoline. Oak Ridge estimates that in 1980 snowmobiles used 323 million gallons of gasoline (40.4×10^{12} Btu). This accounted for 0.3% of the gasoline used in transportation. The average annual gasoline consumption of a snowmobile is estimated by the ISIA (1982) to be 26.8 gallons.

10.4 SERVICE ACTIVITY LEVEL

Information describing the activity of this sector was lacking in the literature.

TABLE 10.1. R&D Applications Summary - Snowmobiles

Data Item/ Fuel Type	UPHS Average Efficiency 1980	# Unit Process Hardware Systems 1980	# Unit Process Hardware Systems 2000	Fuel Consumption Demand (Btu) 1980	Fuel Consumption Demand (Btu) 2000	Product or Service Activity Level (ton-miles) 1980	Product or Service Activity Level (ton-miles) 2000
Gasoline	19%	1,880,000 (1978)	--	40.4×10^{12}	--	--	--

TABLE 10.2. Market Data Summary - Snowmobiles

Data Item/ Fuel Type	Total # Unit Process Hardware Systems 1980	Total Projected # Unit Process Hardware Systems 2000	# UPHS Due to Industry Capacity Expansion (Increased Service Demand) 2000	# UPHS Due to Replacement of Obsolete Units 2000	# UPHS from 1980 Remaining in Service 2000
Gasoline	1,880,000 (1978)	--	--	--	--

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