ECUT Energy Data Reference Series: Lightweight Materials for Ground Transportation

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D. R. Johnson**

July 1984

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ECUT ENERGY DATA REFERENCE SERIES:
LIGHTWEIGHT MATERIALS FOR GROUND TRANSPORTATION

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D. L. Brenchley
Project Manager

PREFACE

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

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

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

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

This volume relates to lightweight materials for ground transportation. Research in this area would investigate techniques to alloy magnesium and to measure the properties of such alloys. In addition, the feasibility of creating and using metal matrix composites would be investigated. These efforts would be directed at reducing the weight of the vehicle.

Other volumes in the ECUT Energy Data Reference Series include:

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

Abarcar, R. B., G. J. Hane and D. R. Johnson. 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. DeBellis. 1984. State of Technology of Direct Contact Heat Exchanging. PNL-5008, Pacific Northwest Laboratory, Richland, Washington.
- Vitullo, M., C. Winter and D. R. Johnson. 1984. The Executive Information System. PNL-5190, Pacific Northwest Laboratory, Richland, Washington.

BACKGROUND ON ECUT ENERGY DATA REFERENCE SERIES

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

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

METHODOLOGY

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

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

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

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

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

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

SCOPE

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

DATA ITEMS

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

Unit Process Hardware System

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

Efficiency Estimates

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

Capital Stock Information

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

Fuel Consumption Demand

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

Product or Service Activity Level

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

SUMMARY

This report summarizes information that describes the use of lightweight materials in automobiles. The information on this mode of transportation represents the largest potential energy savings for substitution of lightweight materials in the transportation sector. Included are data on energy conversion efficiency of the engine and its relationship to vehicle weight, the capital stock, the amount of energy used, and the service activity level as measured in ton-miles. This information is summarized in Tables S.1 and S.2.

TABLE S.1. R&D Applications Summary - Automobiles

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
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 S.2. Market Data Summary - Automobiles

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

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1.0 LIGHTWEIGHT MATERIALS FOR GROUND TRANSPORTATION

To determine the impact of lightweight materials on ground transportation, one must first establish the breakdown of materials composition of the various transportation modes. This volume concentrates on characterizing the materials composition of the automobile transportation system and establishing the potential for energy conservation by using lightweight materials; much less is known, and therefore reported, on the other transportation modes.

Until 1977, the U.S. passenger car models offered by competing manufacturers had evolved into similar classes of vehicles in terms of size, performance, and component characteristics. Competition that centered on performance, comfort, convenience, and luxury led to gradual, incremental changes in size and weight. After the 1973 oil embargo, the escalation of fuel prices made fuel economy a significant competitive factor. By 1977, overall downsizing of vehicles began in earnest as a means to reduce weight and, thereby, increase fuel economy. The trend towards vehicle weight reduction should continue as a result of regulations on fuel economy, emissions, noise, and safety.

Of the energy released by the combustion of the fuel-air mixture in an automotive Otto cycle gasoline engine, only 25% is available at the engine crankshaft and is useful in the operation of the vehicle (see Section 1.2). The distribution of this available energy [brake horsepower (bhp)] in a typical automobile for the EPA composite driving cycle (JPL 1975) is shown in Figure 1.1. The energy uses that are directly proportional to weight are the tire rolling friction (24.7%) and the power to accelerate the vehicle. The power required to accelerate the vehicle is directly proportional to the kinetic energy dissipated at the brakes (12.6%) by virtue of the first law of thermodynamics. The energy uses influenced by the engine size (horsepower) are fuel consumed while coasting and idling (16.3%) and transmission losses (12.1%). Since the required level of performance is attained by making the engine horsepower roughly proportional to the weight, transmission losses and coasting/idling fuel consumption are indirectly but significantly influenced by weight. Aerodynamic drag area varies, but not proportionately with weight. On the average, 65.7% of the available bhp is associated with the weight of the car. Therefore, fuel economy can be improved by reducing vehicle weight.

FIGURE 1.1. Typical Automobile Energy Requirements for the EPA Specified Composite Driving Car (JPL 1975)

The dominant strategy adopted by the automobile industry in improving fuel economy has been to reduce vehicle weight through downsizing and materials substitution. Downsizing has been accomplished by packaging the main vehicle components more closely, reducing interior waste space, reducing the width, shortening the trunk overhang, and reducing styling-induced waste space forward of the firewall. In the smallest car categories, the most practical way of packaging power train components was the front engine, front-wheel-drive layout. Weight reduction via downsizing becomes more difficult as the car becomes smaller and the design of the components approaches the optimum. Further reduction in vehicle weight is then achieved through materials substitution.

Materials substitution is a slower process than simple size changes. The time required to phase new materials into a production automobile is shown in Figure 1.2 (Paul 1979). Although there appear to be no major technical problems with downsizing, there are technical limitations on materials substitution. These limitations are associated with the performance requirements for the part using the substitute material, with feasibility of fabrication,

FIGURE 1.2. Introduction of New Materials for Automotive Applications (Paul 1979)

and with assembly of the part into the automobile at a production rate. Specific components, as well as the entire vehicle structure, must meet individual component and overall system design criteria for rigidity, strength, and dynamic response; lightweight materials can be substituted only when the capabilities of the components made of these materials can meet or exceed the required criteria. Substitution concepts sometimes entail redesign of associated parts as well as principal parts. Component designs and fabrication procedures that are compatible with other manufacturing processes used in automobile production must be developed. Materials substitution must also take into consideration other factors such as cost, appearance, and durability.

1.1 STATUS OF MATERIALS USE IN THE AUTOMOBILE

Data on the materials composition of automobiles in the different weight classes are not readily available. However, data on the typical or average U.S. car (fleet average weight for a given production year) are reported (Wards 1980, 1981, 1982; MVMA 1982). This makes the typical automobile a relevant and

appropriate unit process hardware system (UPHS). In this section, the current materials used in the typical automobile and the potential areas in which substitution would result in direct reduction of the overall vehicle weight will be identified. The impact of research and development of materials that can be directly substituted for conventional materials can then be quantified by estimating the savings in energy as a result of improved fuel economy.

The trend in materials use or distribution in a typical U.S.-built car of the years 1976 to 1982 is shown in Table 1.1 (Wards 1980, 1981, 1982). In the last six or seven years, the domestic automobile industry's new models have been introduced with some noteworthy achievements in lightweight applications. Many of the new applications for plastics, aluminum, high-strength steel, and magnesium were instituted at a penalty in material costs and in the expense of new tooling (Wards 1980, 1981, 1982). This strategy was employed to help put the new cars into the desirable weight classifications and to achieve improvements in fuel economy.

TABLE 1.1. Estimated Materials Consumption in a Typical U.S.-Built Car (pounds) (Wards 1980, 1981, 1982)

Material	1982	1981	1980	1979	1978	1976
High-strength steel	203.0	190.0	175.0	150.0	133.0	120.0
Aluminum	134.0	130.0	130.0	119.0	112.5	85.5
Plastics	200.0	198.0	195.0	185.0	180.0	162.5
Glass	84.0	83.0	83.5	85.0	86.5	87.5
Copper	28.0	27.5	28.0	28.5	29.0	32.0
Zinc die castings	15.5	17.0	20.0	25.0	31.0	44.0
Rubber	135.0	133.0	131.0	137.5	146.5	153.0
Lead	23.5	22.5	23.0	24.0	25.0	25.0
Stainless steel	27.0	26.5	27.5	27.0	26.0	28.0
Iron	461.0	470.0	484.0	498.0	512.0	562.0
Plain carbon steel	1469.0	1602.0	1737.0	1846.0	1915.0	2075.0
Fluids, lubricants	179.0	175.0	178.0	189.0	198.0	190.0
Others (alloy steel, cloth, cardboard, etc)	<u>155.0</u>	<u>153.0</u>	<u>151.0</u>	<u>162.0</u>	<u>175.0</u>	<u>196.0</u>
Total	3114.0	3228.0	3363.0	3475.0	3569.5	3760.5

The broad categories of primary materials used in the manufacture of cars, together with their relative contribution in an average 1975 vehicle, are shown in Table 1.2 (Energy Resources Council 1976). In the Federal Task Force Report (Energy Resource Council 1976), which seeks to establish the motor vehicle goals beyond 1980, a baseline motor vehicle weight configuration was established through an analysis of the weight composition of a number of 1975/1976 and prior model year vehicles. This analysis showed that the proportion of each material used has remained substantially the same since 1955. To set the goals beyond 1980, weight-conscious and innovative structure goals were defined for comparison with the baseline weight configuration. The weight-conscious configuration is achieved through downsizing without sacrificing interior space, while the innovative structure is achieved by increasing use of plastic/aluminum from 10% to 15%. The weight-conscious and the innovative automobile configurations are compared with the baseline configuration in Figure 1.3 and Table 1.3. There was no distinction between the relative material content of the weight-conscious vehicle and the 1975 baseline configurations. However, the relative contribution of steel is expected to decrease to 57% in the case of the innovative vehicle.

TABLE 1.2. Materials in the 1975 Automobile (Energy Resources Council 1976)

<u>Material</u>	<u>Percent of Average Auto Weight</u>
Iron Castings:	
Gray	12.0 - 13.0
Malleable and nodular	4.0 - 5.0
Steel:	
Carbon	53.0 - 55.0
Galvanized	1.5 - 2.0
Aluminized	0.8 - 1.0
Alloy	2.5 - 3.0
Stainless	0.4 - 0.5
Other:	
Aluminum	2.2 - 2.5
Zinc	0.8 - 1.0
Copper	0.5 - 0.7
Lead	0.7 - 0.9
Glass	2.0 - 2.5
Rubber	4.5 - 5.3
Plastics	3.0 - 3.7
Miscellaneous materials	7.9 - 9.5

FIGURE 1.3. Average Motor Vehicle Material Composition by Weight (Energy Resources Council 1976)

TABLE 1.3. Comparison of Baseline and Goal Material Content in Motor Vehicles (Energy Resources Council 1976)

Material	Current Vehicle	Weight Conscious Vehicle	Innovative Vehicle
Steel	60.0%	60.0%	57.0%
Iron	13.0%	13.0%	10.0%
Rubber	3.8%	3.8%	3.8%
Plastics	2.7%	2.7%	2.7%(a)
Aluminum	2.4%	2.4%	8.3%(a)
Glass	2.3%	2.3%	2.3%
Other	15.8%	15.8%	15.9%
Total	100.0%	100.0%	100.0%

(a) The total aluminum/plastic material content of an innovative motor vehicle structure is estimated to be about 11%. The breakdown between plastic and aluminum will be strongly sensitive to cost and availability of material.

Table 1.1 shows that the contribution of steel has dropped from 59% in 1976, to 58% in 1980, and 55% in 1982. The contribution of plastic/aluminum in the 1982 car is approximately 11%. The 1982 car is therefore already close to the conceptual innovative configuration in the relative contributions of steel and plastic/aluminum, and is comparable to the weight-conscious configuration in total weight.

The candidate substitute automotive materials, their potential for direct weight reduction, and the relative material cost (DOT 1979) are given in Table 1.4. The table summarizes the ranges in percent vehicle weight reduction achieved through application of the various materials. The weight reduction potential was estimated in relation to materials (e.g., steel, cast iron, or glass) used in the 1978 model year car. High-strength, low-alloy steels have a potential to reduce vehicle weight by as much as 15% to 30% at approximately the same cost as the original material.

Research areas for the alternative materials (DOT 1979) that will accelerate the substitution are given in Table 1.5.

1.2 EFFICIENCY ESTIMATE

The efficiency with which the energy content of the liquid fuel is converted to the motive power that propels an automobile over distance is illustrated in Figure 1.4 for a passenger car driven in a specified EPA cycle. At Level 1 the energy content of the fuel, released through the thermo-chemical process of combustion in a thermodynamic Otto cycle, is not all available to push against the pistons. Twenty-nine percent (29%) is not available by virtue of the second law of thermodynamics and must be rejected to a heat sink (in this case, to ambient air via cylinder cooling and radiator fan heat rejection); 33% of the energy contained in combusted and unburned fuel goes out with the gases exhausted from the cylinder, the Otto cycle being an open-cycle power system.

At the second level of conversion (Level 2), the 38% of initial fuel energy applied to pushing on pistons is shown to be distributed as follows: 3% is dissipated as the piston rings rub against the cylinder walls; 6% is

TABLE 1.4. Candidate Alternative Automotive Materials (in percent)
(DOT 1979)

Material	Weight Reduction Potential (a)	Relative Material Cost Per Part Based on Current Technology (b)
Wrought Metal		
Low-carbon steel (LCS)	--	1
Dent-resistant steels	10 to 20	0.8 to 1
High-strength/low-alloy steel	15 to 30	0.9 to 1.1
Ultra-high-strength steel	40 to 50	0.7 to 0.8
Aluminum (Al)	50 to 60	1 to 3
Metal Castings		
Grey iron	--	1
Al die casting	50 to 60	0.9 to 1.2
Al permanent mold casting	50 to 60	1.5 to 1.9
Zinc die casting	10 to 40	0.7 to 1.1
Magnesium die casting	75	2.5
Plastics (relative to LCS)		
Unidirectional fiberglass reinforced polyester or epoxy resin	50	2
Sheet molding compound, random fiberglass- reinforced polyester resin	35 to 50	1.15
Unidirectional graphite fiber reinforced epoxy resin (hybrid reinforcement with fiberglass, where possible)	60 to 70	1.5 to 4 ^(c)
Continuous fiberglass reinforced nylon "STX" hot stampable sheet	35	1.5 to 4 ^(d)
Transparent materials		
Glass	--	1
Polycarbonate	40	1.4

(a) with respect to materials such as steel, cast iron, or glass used in the 1978 model year car

(b) material cost only, not including direct labor or variable manufacturing burden

(c) based on a projected cost for graphite of \$6/lb, present cost \$20/lb

(d) project values.

TABLE 1.5. Materials Technology - Illustrative Research Areas (DOT 1979)

Steel

Improved materials properties

Advanced high-strength, multiphase, ferrous-based alloys

Improved materials/processes for corrosion prevention

Improved manufacturability

Forming research and development

Joining

Aluminum

Lower cost of raw materials (including new refining processes)

Improved materials properties

Corrosion resistance

Fatigue resistance

Stiffness

Improved manufacturability to reduce cost

Formability

Joining

Finishing

Data and manufacturing experience to increase designer's confidence

Plastics and Composites

Lower cost raw materials

Materials based on renewable feed stocks

Lower cost reinforcing graphite fibers

Improved materials properties

Develop materials with overall improvement in properties

Develop high-temperature resins

Develop stronger and stiffer fibers

Develop/design optimized hybrid composites

Analyze resin/fiber interface

Improved manufacturability to reduce cost

High-speed, short-cure cycle molding processes

Thermoplastic preforms

Joining

TABLE 1.5. (contd)

Plastics and Composites (Continued)

- Fabricate larger parts
- Finishing
- Non-destructive testing (NDT)
- Increased designer confidence
- Fatigue properties
- Reliability and durability of composite parts
- Crashworthiness
- Engineering properties and design criteria
- Environmental impacts
- Recycling
- Non-toxic substance emitting materials
- Health hazards due to fibrous reinforcements

Foam-Filled and Multimaterial Composites and Other Materials

- Foam core structural components
- Low-cost manufacturing process for magnesium
- Metal matrix composites
- Optimized multimaterial systems

Improved Glazing

- Elimination of lacerations upon impact (windshields, side and rear glazing)
- Improved strength for structural purpose and weight reduction

expended in inducting the air-fuel mixture and in exhausting the products of combustion; 4.5% is dissipated as other friction losses such as crank, pin, and connecting rod friction. Only the remainder, 25%, is available at the crankshaft for delivery to the wheels to move the automobile and its load. This is the bhp shown in Figure 1.4.

Not all the power (energy) available at the crankshaft is available to propel the automobile. Two percent (2%) is necessary to operate such components as the alternator, air pump, cooling fan and water pump, and 0.5%

FIGURE 1.4. Energy Use in Passenger Car During EPA Cycle (Hopp 1981)

for power steering, if used; 1.5% is dissipated as losses at the transmission and differential gears; 1.5% is dissipated as frictional losses at the wheel axle bearings; 6% is expended to overcome tire rolling friction; 6% is dissipated to overcome aerodynamic drag; and approximately 4% is spent to keep the engine running (coast and idle). Of the total energy released by the fuel during combustion, only 3.5% is seen to be available to move and speed up the vehicle and its load (the equivalent of this is the energy subsequently dissipated at the brakes). (See Figure 1.1 for the distribution of the automobile energy requirements as a percentage of the bhp.) The overall impact of vehicle weight reduction on the use of energy (as shown in Figure 1.4) can be summarized as follows:

- Weight reduction will have a direct impact on energy use at Levels 3 and 4.
- Energy use at Level 2 is affected indirectly by weight reduction. This is a consequence of the engine response to a given load, i.e., on the engine operating point on a bhp-rpm diagram (see Figure 1.4) that is affected by both the total weight (car + load) and vehicle speed (mph).
- Energy use at Level 1 is affected only minimally inasmuch as the engine heat sink temperature is maintained more or less constant by a thermostat in the cylinder cooling circuit that provides a more or less constant rate of heat rejection. Energy lost with the exhaust gases can be affected by the engine operating speed.

A typical fuel consumption map for a car equipped with an Otto-cycle engine is shown in Figure 1.5. The effect of engine load (i.e., total weight of the car, passengers, and baggage, and the speed of the car) on the engine operating point and fuel consumption [i.e., brake-specific fuel consumption (bsfc) in lb fuel per bhp-hr] can be demonstrated by tracing the progression of the curve labeled "typical fixed-gear road load horsepower curve for 3500-lb car." As the car speeds up from zero to 70 mph, the bsfc decreases from greater than 0.80 to about 0.55 lb fuel per bhp-hr. Speeding the car up further to 80 and 90 mph increases the fuel consumption to 0.57 and 0.66 lbs fuel per bhp-hr.

FIGURE 1.5. Typical Fuel Consumption Map for Otto Cycle Engine (JPL 1975)

The brake thermal efficiency, η_b , is computed from the bsfc using the following equation:

$$\eta_b = 2545 / (\text{bsfc} \cdot h_f) \quad (1)$$

where h_f = heating value of the fuel, Btu/lb_m of fuel

Using the example of Figure 1.5, a 3500-lb car running at 25 mph in the city has the engine operating at a bsfc of 0.80 lb gasoline per bhp-hr, a thermal efficiency of 16.8% [using Equation (1)] and a heating value of 18,900 Btu/lb_m of gasoline. Highway driving at 55 mph results in a bsfc of 0.59 lb gasoline per bhp-hr with the corresponding brake thermal efficiency of 22.8%.

The effect of acceleration has not been factored in this illustration. The average thermal efficiency of the automobile over a specified driving cycle will depend on the time the automobile spends at one particular operating point. As the car speeds up and slows down, the thermal efficiency at specific operating points, weighted by the specific time spent at that point, summed over the total operating time, should give an average thermal efficiency. A car with an optimum hp-to-weight ratio should provide satisfactory acceleration and at the same time allow the car to attain the optimum operating bsfc sooner. Less residence time at a higher bsfc should improve the overall brake thermal efficiency. The effect of weight reduction for an automobile will be to increase brake thermal efficiency for two reasons: 1) lower bsfc than the 3500-lb car at any given speed, and 2) less residence time (due to faster acceleration) at higher bsfc. A heavier car will operate in a curve lower than that shown for the 3500-lb car. The combination of heavier load and slower acceleration will cause the car to operate at higher bsfc with longer residence time, resulting in higher overall bsfc and lower overall brake thermal efficiency.

When considering a bigger engine (i.e., 8 cylinders versus 6 cylinders versus 4 cylinders), one should bear in mind that different fuel consumption maps should be used. The increase in engine output is in discrete steps and the hp-to-weight ratio is changed. To move the same load, the bigger engine will operate at the lower rpm range for the same driving cycle and will be generating the same overall power output at a higher bsfc. Thus, it is expected that an automobile equipped with an engine for a suitable hp-to-weight ratio (approximately 0.03 hp per lb weight) will operate at a higher overall brake thermal efficiency than a similar one equipped with the next available higher hp engine with more cylinders.

Fuel economy is of vital concern to the automotive industry because of the Energy Policy and Conservation Act passed into law on December 22, 1975. This act mandated a production-weighted Corporate Average Fuel Economy (CAFE) for passenger automobiles to increase from 18 mpg in 1978 to 27.5 mpg in 1985. The CAFE standards can be met either by using more efficient power plants or by using lighter weight automobiles. Alternative power plants improve the fuel

economy by providing higher efficiencies of energy conversion; lightweight materials improve the fuel economy by improving the efficiency of energy utilization. As illustrated in the previous paragraphs, the engine is made to operate at the conditions where the engine output meets the requirements of the load (i.e., total weight to be moved and the speed). In considering the impact of using lightweight materials in ground transportation, it should be assumed that automobile systems are similarly equipped, powerwise, and improvements in energy utilization therefore come as improvements in fuel economy, measured in mpg.

The functional relationship between fuel economy, vehicle test weight, and rated engine horsepower is given by the following equation (Energy Resources Council 1976):

$$F_e = A (W)^{-a} (Hp/W)^{-b} \quad (2)$$

where F_e = EPA composite (55% urban and 45% highway driving) fuel economy in miles per gallon (mpg)

W = Test weight of the vehicle, defined as curb weight plus 300 lb

Hp = Rated engine horsepower, bhp

Hp/W = Ratio of the rated engine horsepower to the auto test weight; a value of 0.03 is necessary for an accepted level of performance

A, a, b = Scaling coefficients that are functions of engine characteristics.

For a vehicle equipped with a standard gasoline engine, the scaling coefficients derived through a regression analysis of actual 1975/1976 EPA fuel-economy data are (Energy Resources Council 1976):

$$A = 6060; \quad a = 0.88; \quad b = 0.40$$

For vehicles with diesel engines, the values of the scaling coefficients determined from available data of dynamometer tests of diesel engines are (Energy Resources Council 1976):

$$A = 2370; \quad a = 0.69; \quad b = 0.35$$

The vehicle fuel consumption F_c in gallons per mile can be derived from Equation (2), and is given by

$$F_c = (W)^a (Hp/W)^b / A \quad (3)$$

The change in fuel consumption per unit change in vehicle test weight is given by

$$dF_c/dW = (a/A) (W)^{a-1} (Hp/W)^b \quad (4)$$

for the case where (Hp/W) is maintained constant (i.e., level of performance is maintained); or

$$dF_c/dW = (a-b) (W)^{a-b-1} (Hp)^b / A \quad (5)$$

for the case where the engine is not changed, and therefore the Hp is maintained constant.

Using Equation (4) a 3,000-lb test weight vehicle equipped with a gasoline engine such that $Hp/W = 0.030$ hp per lb should expect a fuel consumption change of approximately 1.4×10^{-5} gal/lb-mile. On the other hand, the same vehicle equipped with a diesel engine with $Hp/W = 0.030$ hp per lb will have an estimated fuel consumption change of 7.1×10^{-6} gal/lb-mile.

Because of weight propagation effects, care should be taken in estimating direct weight savings through substitution of lightweight materials for steel. The direct removal of 1 lb of original material from the automobile structure can result in a reduction of greater than 1 lb in the curb weight of the automobile because the requirement for suspension and support structure will also be reduced. The reduction in required engine power and, consequently, engine weight, will also result in decreased curb weight. Estimates of the weight propagation factor range from 1.4 to 2.6 (ARGOS 1978). A car manufacturer

recently achieved a 0.76 secondary weight reduction ratio (corresponding to a weight propagation factor of 1.76) in an advanced concept lightweight vehicle (Cummings-Saxon 1981).

1.3 CAPITAL STOCK INFORMATION

1.3.1 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 1.6.

TABLE 1.6. Automobile Stock in 1980 by Size Category

<u>Category</u>	<u>Number</u>	<u>Percent of Total</u>
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%

Information describing the sales of domestic and imported automobiles in 1980 is shown in Table 1.7. The table shows that subcompact cars had the largest share of the market at 38.0%, with midsize following at 33.7%, and large cars third at 13.4%. This is a notable market shift from 1978 when midsize had the largest share of the market at 31.6%, followed by large and subcompact 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 1.8.

Information on the survival and scrappage rates of automobiles is illustrated in Figure 1.6 and Table 1.9. The survival probability curve for automobiles as a function of their age is shown in Figure 1.6. One can see from the figure that the "half-life" for automobiles is approximately 10 years. Points on the curve are tabulated in Table 1.9, which also presents information on scrappage rates, the number of vehicles in operation, and the percent of vehicle-miles traveled (by age group).

TABLE 1.7. 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 D60.

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

(c) Includes federal government vehicles.

(d) Not available.

(e) Shipments only.

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

(g) Includes heavy-heavy.

TABLE 1.8. Market Shift in Automobile Sales Between 1978 and 1980 (Oak Ridge 1981)

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

FIGURE 1.6. Survival Probability Curves for Automobiles and Light Trucks (Oak Ridge 1981)

TABLE 1.9. Automobiles in Operation, Scrappage Rates, and Vehicle Travel
by Age of Vehicle, 1980 (Oak Ridge 1981)

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

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

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

1.3.2 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 1.10). The annual growth rates ranged from 1.2% to 1.9%.

TABLE 1.10. Projections of Automobile Stock in 2000.
(Knorr and Millar 1979, Millar et al. 1982)

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

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 1.11. In Case A, approximately 110 million of the automobiles would be powered by gasoline engines, and

TABLE 1.11. Summary of Projected Automobile Ownership, Use, and Energy Demand

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

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.

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.

1.4 FUEL CONSUMPTION DEMAND

1.4.1 Fuel Consumption Demand, 1980

Argonne (Millar et al. 1982) estimates that in 1980 automobiles consumed approximately 77.9 billion gallons of gasoline, or $9,740 \times 10^{12}$ Btu. By

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

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

1.4.2 Fuel Consumption Demand, 2000

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

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

1.5 SERVICE ACTIVITY LEVEL

1.5.1 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 (see Table 1.1). 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.

1.5.2 Service Activity Level, 2000

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

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