Industrial Ecology of the Automobile: A Life Cycle Perspective

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and mobility needs in a sustainable manner.*

Preface

In 1993, the AT&T Foundation recognized industrial ecology as an emerging field capable of guiding future efforts to reduce the environmental impacts of manufacturing processes and products. Integrating pollution prevention, environmentally conscious design, and industrial ecology into university science and engineering education and research is a central objective of the Foundation's environmental program. The National Pollution Prevention Center (NPPC) at the University of Michigan received one of six AT&T Industrial Ecology Faculty Fellowship awards in October 1994. With this funding, the NPPC sponsored an interdisciplinary graduate course on industrial ecology, developed an industrial ecology educational resource compendium, researched the environmental impacts of high-definition display technology, and conducted the Industrial Ecology of the Automobile Seminar Series. We wish to thank the AT&T Foundation for sponsorship of this research and other pioneering work in the field of industrial ecology.

The Seminar Series examined the environmental burdens and impacts of automobiles by addressing each automobile life cycle stage—from materials selection to vehicle retirement— in separate sessions. Policies and regulations affecting each of these stages were also analyzed. Topics addressed in the Seminar are presented below.

Participation in the Seminar was interdisciplinary by design. The NPPC recognizes that workable solutions to the complex problem of reducing the environmental impact of the automobile will require the efforts and expertise of professionals from manufacturing; federal, state, and local regulatory bodies; environmental groups; materials and parts suppliers; and academia and research organizations. A list of the participants and speakers for the seminar series is provided in Appendix 1.

The objective of the Seminar Series was to bring together different stakeholders and disciplines to better understand and ultimately improve the relationship between the automobile and the environment. By fostering discussion among disparate stakeholders interested in all aspects of the automotive industrial system, the Seminar was intended to achieve the following:

- Exchange of information and development of communication across disciplines
- Improve understanding, interaction, and disclosure among stakeholders
- Identify tradeoffs between environmental and other criteria (cost, performance, etc.)

Topic	**Seminar Session Title**
Overview of Life Cycle Framework	Introduction to Industrial Ecology and Life Cycle Design
Raw Material Acquisition and Processing	Materials Selection
Assembly and Manufacture	The Auto in Production: Pollution Prevention in Automobile Manufacturing
Use and Service	The Auto in Use: Fuel Economy and CAFE Standards
Use and Service	The Auto in Use: Emissions
Retirement	The End of the Auto Life Cycle: Reuse and Recycling
Total Life Cycle Burdens/Opportunities for Improvement	Future Directions for Government and Industry

- Develop options and recommendations for industry and government to incorporate into future policy-making and automobile design and production decision-making.

Each seminar session focused on characterizing the major environmental burdens for each life cycle stage and identifying their sources. In addition, opportunities for reducing these burdens in the context of performance, cost, and legal requirements also were presented and discussed.

This book serves as the capstone of the Industrial Ecology of the Automobile Seminar Series. Although the goal of the Seminar Series was to generate a white paper, the white paper gradually evolved into this book. The broad scope and complexity of the automobile life cycle led to development of a more extensive manuscript. This book presents and analyzes the major findings of the Seminar Series. In addition, relevant topics that were not covered in the Seminar Series because of time constraints are considered. Using the life cycle framework, this book broadly assesses and characterizes the environmental burden associated with the automotive product system. The role of technology, policy, and consumer values and behavior in affecting environmental burdens and the opportunities for reducing those burdens are identified. Discussion focuses on environmental, policy, and design aspects of the system and, to a lesser extent, economic and social issues. Costs are considered broadly in terms of the cost-effectiveness of various alternatives for improvement.

This book uses existing literature and data from government, industry, and other published sources. Tradeoffs between environmental criteria and other system requirements that influence the design and management of the automobile life cycle also are analyzed. A survey of public policies and regulations examines how current policies may provide different stakeholders incentives or disincentives to improve environmental performance.

An exhaustive literature search, however, was not conducted. We relied partially on the direction of seminar participants for identification of key issues and references. It is difficult to capture each of the sometimes divergent stakeholder perspectives in a single monograph. In reading this book, emphasis should be given to understanding stakeholder differences and the complexity of the automobile life cycle system.

We fully acknowledge the incompleteness of this work but offer it as a new approach to improving the design and management of the automobile life cycle system.

We wish to recognize the many important contributions made toward the development of this book. During the Seminar Series, lectures were presented by the following individuals: Sandra Brewer (Energy and Environmental Staff–General Motors Corporation), Mia Costic (Scientific Research Laboratory–Ford Motor Company), Harry Foster (Economic Analysis Department–General Motors Corporation), John German (National Vehicle and Fuel Emissions Laboratory–U.S. Environmental Protection Agency), Roger Heimbuch (Materials and Fastening Engineering–General Motors Corporation), Philip Lorang (National Vehicle and Fuel Emissions Laboratory–U.S. Environmental Protection Agency), Dick Osterberg (Huron Valley Steel), Chris Porter (Environmental Quality Office–Ford Motor Company), and Marc Ross (Physics Department–University of Michigan). Their presentations provided an important basis for our research. In addition, Amory Lovins (Research Director–Rocky Mountain Institute) shared his vision for the future of the automobile by offering a provocative keynote lecture on the "hypercar" during the final Seminar. Robert Frosch (J.F. Kennedy School of Government—Harvard University) kindly moderated a three-hour presentation and discussion of the Seminar Series results and conclusions.

We wish to express sincere thanks to the following individuals for providing review comments: Jeff Alson, Sandra Brewer, Janet Cohen, David Cole, Terry Cullum, Susan Day, Jerry Fosnaugh, Bernd Gottselig, Charles Griffith, Roger Heimbuch, Robert Kainz, Troels Keldmann, Philip Lawrence, Amory Lovins, Scott Noesen, Hans Posselt, Richard Porter, Michael Sabourin, Anita Singh, Larry Slimak, John Sullivan, Robert Stephens, and Ronald Williams. The research, editing, and graphics provided by Eric Arons, Julie Gehrman, Rebaccah Kamp, Dan Menerey, Douglas Moody, and Peter Reppe of the National Pollution Prevention Center are greatly appreciated.

Many of the issues discussed in this book are highly controversial. We attempted to accurately represent the various perspectives and interests of the key stakeholders responsible for the life cycle design and management of the automobile. The opinions and conclusions expressed in this book, however, are not necessarily endorsed by the Industrial Ecology of the Automobile Seminar Series participants and the organizations that they represent.

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Chapter 1

Introduction

Industrial ecology is an emerging field that explores the interactions and relationships between industrial and ecological systems. Although the origin of the term *industrial ecology* is uncertain, major advancements in the field have occurred during the last five to seven years. Publications from industrial ecology conferences and symposia sponsored by the National Academy of Sciences and the National Academy of Engineers,[1,2] as well as recent books,[3,4] demonstrate the level of interest in this field.

A unifying framework for industrial ecology has not been established, but several themes are gaining acceptance for its foundation. These themes include industrial ecology as a metaphor, material and energy analysis, systems analysis, and interdisciplinary problem solving. Appendix 2 presents several definitions of industrial ecology that express a range of perspectives and goals.

Robert Frosch has put forth the concept of industrial ecology as a metaphor[5]:

> The industrial ecosystem would function as an analogue of biological ecosystems. (Plants synthesize nutrients that feed herbivores, which in turn feed a chain of carnivores whose wastes and bodies eventually feed further generations of plants.) An ideal industrial ecosystem may never be attained in practice, but both manufacturers and consumers must change their habits to approach it more closely if the industrialized world is to maintain its standard of living—and the developing nations are to raise theirs to a similar level—without adversely affecting the environment.

Natural ecosystems can be used as a model for the design and management of industrial systems. For example, natural ecosystems are highly integrated, and by-products from one organism become input materials for other organisms in the food chain. Material processors, suppliers, and manufacturers are analogous to producers, while customers consume industrial outputs in the form of products, and resource recovery managers fulfill the role of decomposers.

Robert Ayres introduced the concept of *industrial metabolism* which also extends the metaphor.[6] Industrial metabolism represents the physical and chemical processes that convert raw materials and energy into finished products and eventually wastes.

Tracking materials and energy flows and transformations is a fundamental approach of industrial ecology. Material and energy accounting is essential for identifying and assessing environmental consequences of industrial activities. Two approaches have been taken, based on different system orientations: a material life cycle[7] and a product life cycle.[8,9] A material life cycle traces a particular element, compound, or mixture through the environment and the economy. For example, patterns of use and the fate of chlorine[10,11] and heavy metals such as lead[12] and mercury[13,14] have been investigated. The product life cycle is a comprehensive system for addressing the full environmental consequences of goods and services that satisfy a particular societal need. A product life cycle encompasses raw materials acquisition, materials processing, manufacturing, use, service, and end-of-life management including resource recovery (reuse, remanufacturing, and recycling) and disposal.

Interest in industrial ecology has been fostered by current trends in resource use, energy consumption, waste generation, and population growth that do not appear sustainable. The potential catastrophic effects from emissions of greenhouse gas[15,16] and ozone-depleting substances[17] also raise concern about our future course.

Many industrial systems can be characterized as linear flows of material that result in resource depletion and waste accumulation. The linear flow of materials also can be considered a dissipative use that may lead to the dispersion of toxic materials. Examples of dissipative uses of material include the loss of tire tread on the road which releases PAHs, perchloroethylene emissions from dry cleaning shops, and mercury releases to the environment from improper disposal of fluorescent bulbs and switches. Material flows of sustainable industrial systems are more cyclical and highly integrated. These systems minimize resource depletion and waste generation and emphasize remanufacturing, reuse, material recycling, and energy recovery.

In addition to the pattern of resource flows, whether dissipative or cyclical, the rate of material and energy use will influence the sustainability of an industrial system. Excessive resource depletion and pollution can gradually overwhelm the ecological processes that compose our life support system.

Several tools have been developed which support practical application of the conceptual framework of industrial ecology. Life cycle assessment,[8,18] life cycle design,[9,19] and environmental management systems[20–22] represent key tools for design and management of sustainable industrial systems. The design and management of industrial systems that are more sustainable ecologically and that address societal needs requires multidisciplinary participation. Changes in technology, consumer values and behavior, and corporate and public policy are necessary to achieve a more sustainable society.

1.1 Characterization of the Automotive Industrial System

The automobile is one of the most resource intensive and influential consumer products of the Industrial Age. Instrumental in the growth of the post-World War II economy in the United States, the passenger vehicle has become the dominant mode of passenger travel in North America. Passenger vehicles include automobiles, light-duty trucks, sport-utility vehicles, and minivans. In this book, *automobile* will denote passenger vehicle.

Although substantial infrastructure exists for public transportation (subways, buses, and commuter rail), intercity rail, aircraft, and bicycles (in some cities), automobile travel accounted for 85% of total passenger-miles traveled in 1990. Aircraft travel accounted for only 10%, and bus and train travel provided less than 5% of total passenger-miles traveled in 1990.[23]

The success of the automobile can be attributed to its ability to uniquely satisfy consumer demands for independence, reduced door-to-door travel time, comfort, reliability, privacy, and enjoyment, in addition to providing personal mobility. The industrial system that produces vehicles to meet the demand for passenger travel is vast in economic and absolute terms. The following list characterizes the breadth and depth of the North American automobile manufacturing sector.[24,25] Foreign models manufactured in the United States are not included in these totals.

Vehicles Sold in the United States, 1993	**"Big Three" Sales, Millions of Dollars, 1993**	**U.S. Capacity, 10^6 Cars and Trucks, 1993**
11,760,000	$290,385	16.9
Assembly Plants, North America, 1993	**U.S. Suppliers to Domestic OEMs**	**Total Employees in Motor Vehicle and Equipment Mfg. (Car, Truck, Bus), 1993**
84	4,000	1,055,968

The infrastructure that supports the use and retirement of the automobile is significant and reflects substantial public and private investment during the past 50 years. The North American road and highway system, consisting of 3.9 million miles of roads, is the most extensive in the world and cost $680 billion in federal, state, and local capital expenditures from 1960 to 1992.[26] This massive highway infrastructure has, in part, facilitated the 40% increase in vehicle miles traveled (VMT) in the United States since 1980. Consumer behavior and growth in population and the vehicle fleet also are principles drivers of VMT increases. In addition, substantial infrastructure also exists for the delivery of automobile fuel, automobile repair and service, and vehicle retirement.

Automobile users constitute a significant part of the automotive industrial system. Consumer demands and behavior help shape the size, styling, and performance of the next fleet of vehicles. They also influence the siting of automobile manufacturing plants, landfills, highways, and the land use patterns that determine commuting distances. Proposed changes in public policy addressing the automobile industry should attempt to estimate consumer responses and manufacturers' reactions.

A complete view of the North American automotive industrial system also considers the system within an international, macroeconomic context. Global automotive manufacturing is oligopolistic in structure, dominated by a relatively small number of large producers. The United States, Japan, Germany, and France accounted for 89% of 1992 world production (31,694,444 passenger vehicles).[24] Additional entry by new competitors is restricted by the extremely high capital requirements needed for entry into the market. South Korea's Hyundai is the only relatively new entrant in the global market to produce more than 500,000 units/year.

In the late 1970s and 1980s, Japanese producers gained considerable market share in the global market with vehicles that were well made, fuel efficient, and inexpensive in comparison to domestic models. To remain economically viable, U.S. producers were forced to drastically reduce capital and labor costs and to make dramatic changes in production techniques, many of which were based on Japanese lean-production methods. The automotive industry also is extremely sensitive to changes in macroeconomic variables such as interest rates, unemployment, inflation, national income, and the balance of trade. The recession of 1990–1991 illustrated how the U.S. industry suffered from lagging sales in spite of dramatic quality improvements and cost reductions.

International trade policy also affects the North American automotive industry. As a result of the highly competitive international context within which U.S. manufacturers operate, design and policy decision-makers must now consider a greater number of more complex issues than in the recent past.

The automobile manufacturing sector, the infrastructure that supports automobile use, and consumers compose the automotive industrial system. In turn, this system exists within the international economy. When invoking the definition of industrial ecology, these systems should be viewed as inextricably linked to one another and to the natural ecosystems in which they operate. Each subsystem is responsible for contributing to activities that adversely affect the environment and public health through the production of waste products, emissions, traffic congestion, and noise pollution. The systems approach of industrial ecology suggests that any change in automotive design, engineering, policy, or regulation aimed at improving one aspect of the system also should be evaluated for its impacts on other system components. Improvements in the environmental performance of the automotive industrial system will result only from those initiatives that can improve the environmental performance of one aspect of the system without degrading other components. Of course, many difficulties lie in identifying effective environmental improvements that also satisfy critical cost and performance requirements. In addition to the cost and performance aspects that are often considered paramount in industry, legal and cultural needs must be met.

Automobiles are an integral part of our society. Although this book is not a comparative assessment of the automotive sector versus alternative modes of transportation, an industrial ecologist may pose the following questions to stimulate broader consideration of the automobile system:

- Should the automobile be promoted as the primary solution for achieving an economically and ecologically sustainable transportation system?
- Many opportunities exist for improving the automobile; however, would investing in alternative systems lead to a more cost-effective outcome when the full costs of the automobile are considered?
- Does the automobile represent the most economically and ecologically sustainable system to meet the transportation needs of developing countries?

This book will not address these questions directly. However, it attempts to enhance our understanding of the full automobile life cycle, which is necessary to improve strategic planning of our transportation system.

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Chapter 2

Life Cycle Design Framework

Life cycle design provides a comprehensive framework for guiding the management and design of sustainable product systems. It is a useful framework for investigating the industrial ecology of the automobile by defining system boundaries, a set of principles, and tools for addressing the objectives of the Industrial Ecology of the Automobile Seminar Series. The life cycle design framework outlined in *Life Cycle Design Guidance Manual*[1] and *Life Cycle Design Framework and Demonstration Projects*[2] served as a basis to organize this study. Key elements of this framework will be presented as background and include the following:

- Product life cycle system
- Goals
- Principles
- Life cycle management systems
- Development process

2.1 Product Life Cycle System

2.1.1 Life Cycle Stages

A product life cycle consists of the following generic stages:

- Materials production
- Manufacturing and assembly
- Use and service
- End-of-life management

Figure 2.1 shows a generalized product life cycle system, and Figure 2.2 shows a generic automobile life cycle.

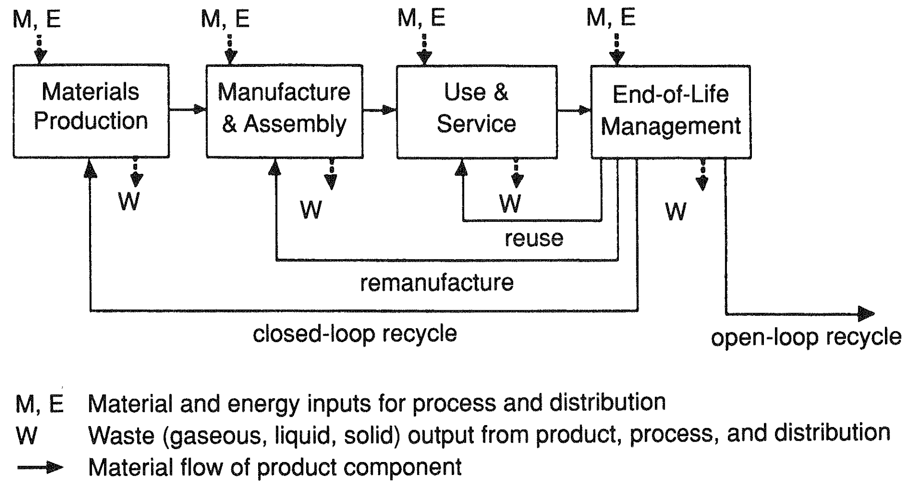


Fig. 2.1 Product life cycle system.

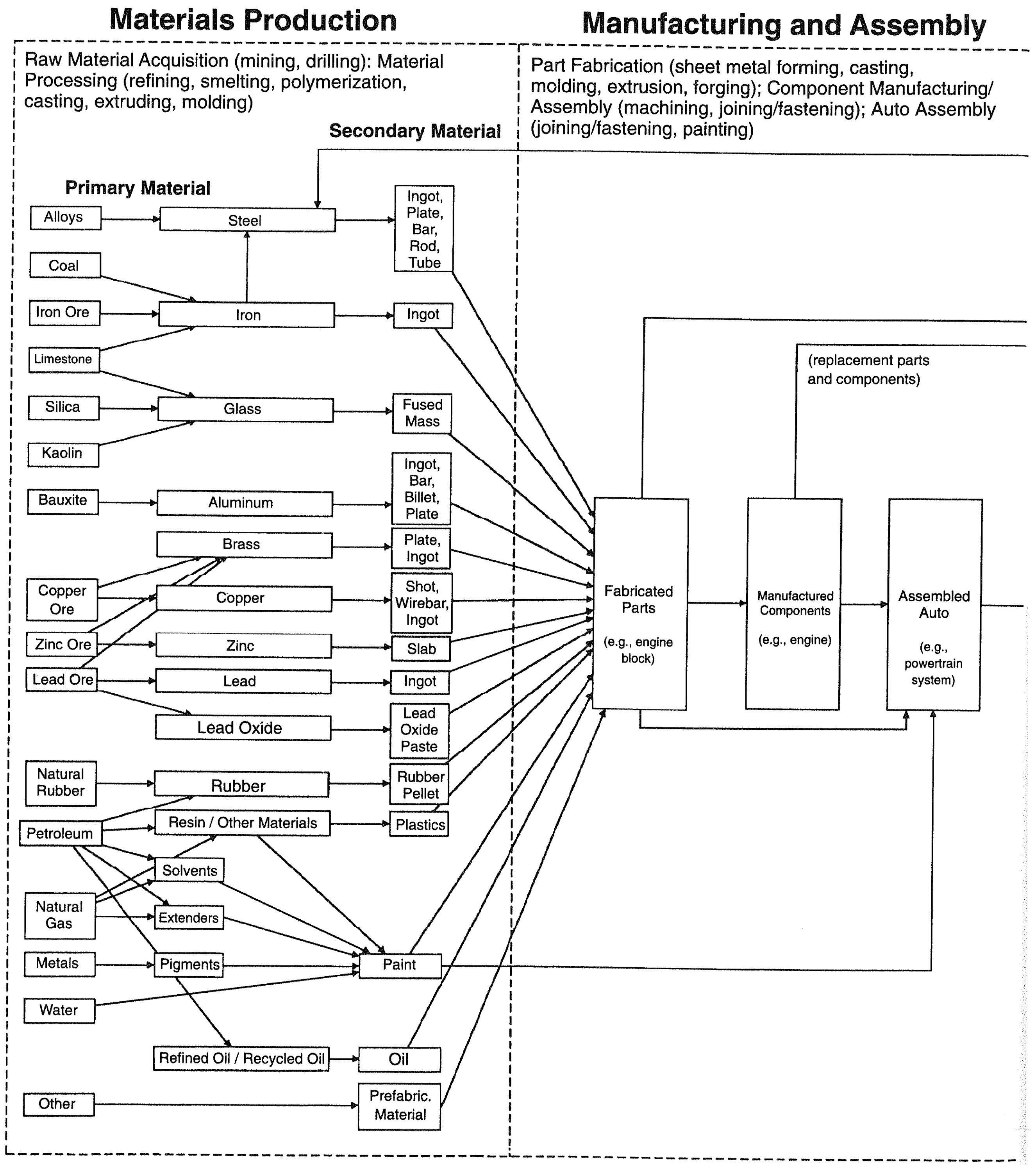


Fig. 2.2 Automobile life cycle.

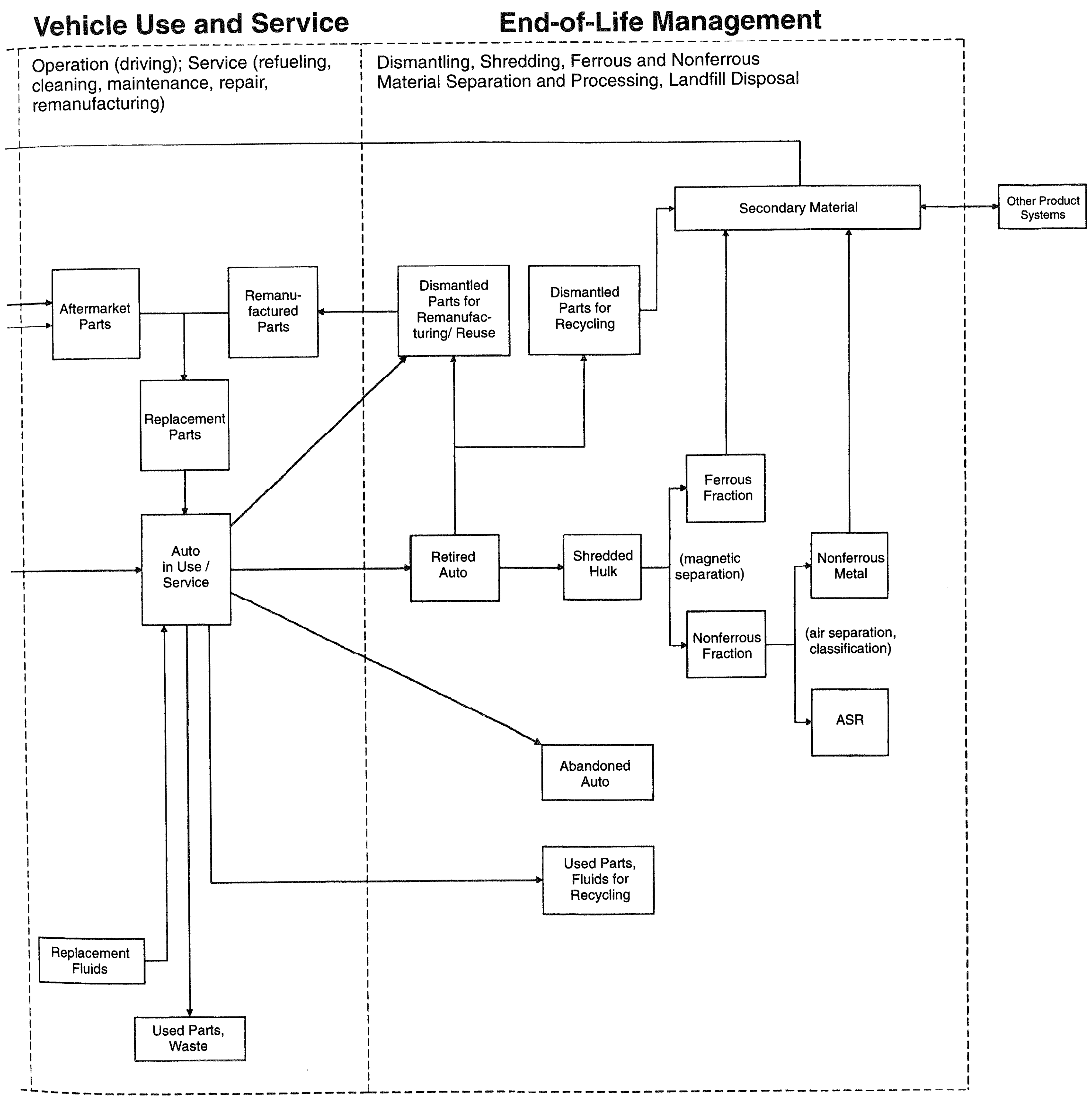


Fig. 2.2 Automobile life cycle (continued).

The primary stages and activities of an automobile life cycle include the following:

Stages	Major Activities and Processes
Materials Production	Collection and processing
Manufacturing	Parts and components fabrication and vehicle assembly
Use	Vehicle operation and service
Retirement	Dismantling (parts reuse, remanufacture, material recycling), shredding (material recycling), and disposal of automotive residuals

Each stage will be addressed in a separate section of this chapter.

The life cycle system is complex because of its dynamic nature and its geographical scope. The useful life of an automobile manufactured today is approximately ten years, and the product development cycle can range from two to four years. The time lag between design and retirement of a vehicle complicates design and planning for optimal vehicle retirement and resource recovery.

Mapping the material and energy flows for the automobile life cycle system on a geographic basis would be an arduous task. It is important to recognize that the environmental consequences of the automobile occur on global, regional, and local levels for each stage and activity.

2.1.2 Product System Components

Product, process, and distribution components further characterize the product system for each life cycle stage. This organization, in contrast to life cycle analysis convention, can better accommodate product and process design functions. Figure 2.3 shows the flow of material and energy through a generic stage or substage. The distribution component which connects consecutive stages or substages is shown in Figure 2.4.

Product

The product component consists of all materials constituting the final product. Included in this component are all forms that these materials may take throughout the various life cycle stages. The product component of a complex product such as an automobile consists of a wide range of materials, which are identified in Chapter 3. These may be a mix of primary (virgin) and secondary (recycled) materials. The materials contained in new or used replacement parts are also included in the product component.

For automobiles, the product component can be organized into the following subsystems: interior, frame, exterior, chassis/powertrain, electrical, and accessories.

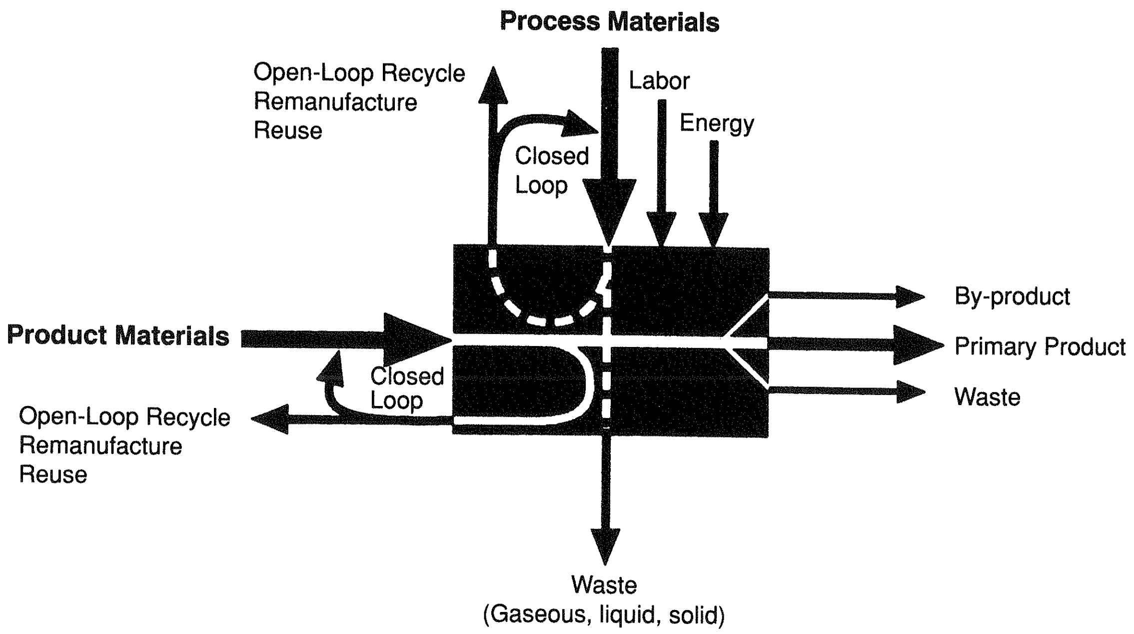


Fig. 2.3 Flow diagram template for life cycle subsystem.

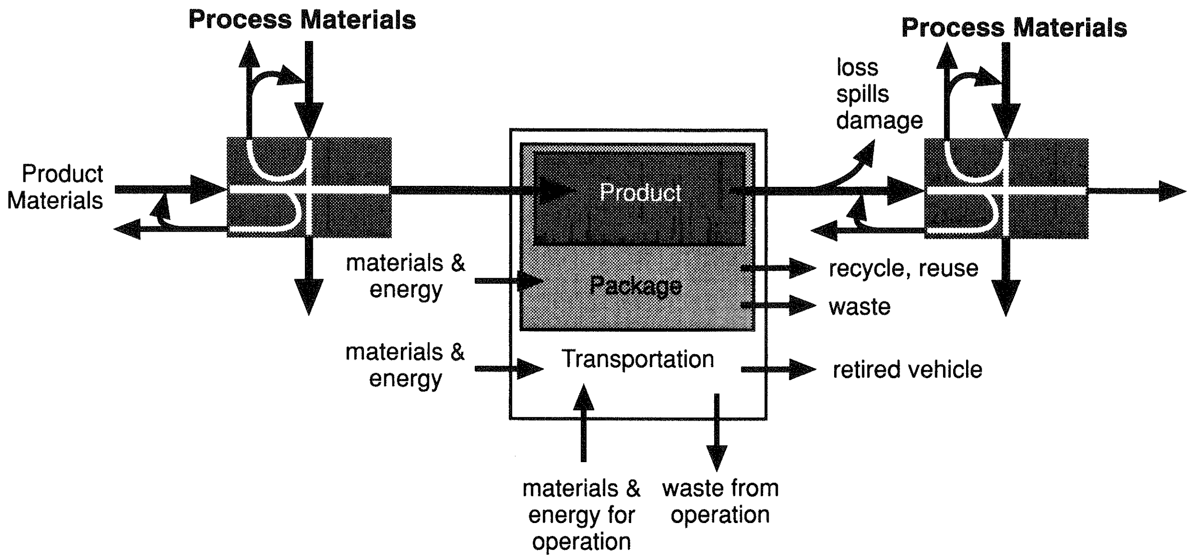


Fig. 2.4 Distribution component flow diagram.

Process

Processing transforms product materials using additional material and energy inputs into final products and eventually into residual materials. The process component includes direct and indirect material inputs that are not significantly incorporated into the final product. Catalysts, solvents, and lubricating fluids are examples of direct process materials; plant and equipment represent indirect material inputs for processing. Each product system consists of many process and distribution components that follow their own product life cycles.

Distribution

The distribution component consists of packaging systems and transportation networks used to contain, protect, and transport the product component. The process and distribution components of the product system share the following subcomponents: facility, plant or offices, unit operations, process or procedures (including administrative services), equipment and tools, human resources, direct and indirect material inputs, and energy.

2.2 Life Cycle Design Goals

The broad goal of life cycle design is to design and manage products that are ecologically and economically sustainable.

Sustainable development meets the needs of the present generation without compromising the ability of future generations to fulfill their needs.[3] Conditions necessary for sustainability include sustainable resource use (conserve resources, minimize depletion of nonrenewable resources, and use sustainable practices for managing renewable resources), pollution prevention, maintenance of ecosystem structure and function, and environmental equity. All of these conditions are interrelated and highly complementary. Economic sustainability requires that the product system must meet basic cost, performance, and legal criteria.

The broad goals of life cycle design are shown in the following list:

Promote Sustainable Resource Use and Efficiency	Recognize that the amount and availability of resources are ultimately determined by geological and energetic constraints, not human ingenuity Conserve resources, minimize depletion of nonrenewable resources, use sustainable practices for managing renewable resources
Promote Pollution Prevention	Use a proactive approach based on source reduction and avoid the release of persistent bioaccumulating toxic chemicals and the transfer of pollutants across media (air, water, and land)

Promote Pollution Prevention (continued)	Address environmental issues in the design stage—one of the most effective approaches to pollution prevention
Protect Ecological and Human Health	Recognize that healthy functioning ecosystems are essential for the planet's life support system Avoid irreversible damage to ecosystems such as the loss of biodiversity and habitat degradation
Promote Environmental Equity	Address the distribution of resources and environmental risks Meet the current needs of society without compromising the ability of future generations to satisfy their needs: intergenerational equity Change patterns of resource consumption and associated environmental risks within developed and less developed countries to achieve sustainable development and to address the disparity among socioeconomic groups within a country: intersocietal equity

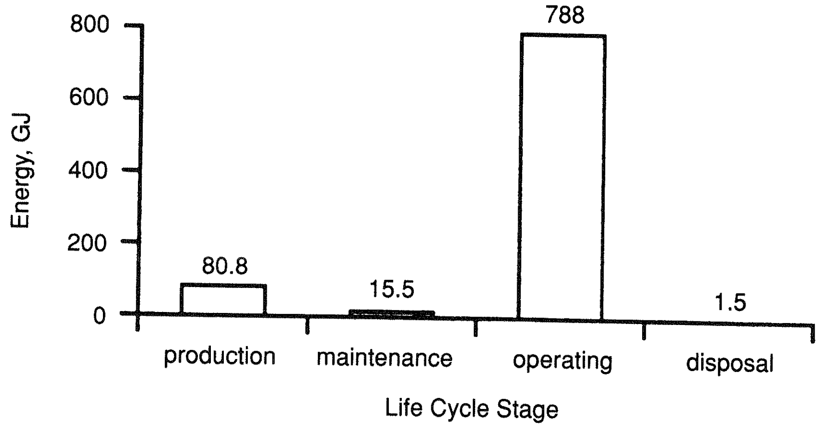
The specific environmental goal of life cycle design is to minimize the aggregate life cycle environmental burdens and impacts associated with a product system. Environmental burdens include resource inputs and waste outputs, which can be classified into impact categories according to life cycle impact assessment methods.[4–7] General impact categories include resource depletion and ecological and human health effects. No universally accepted method for aggregating such impacts is available.

These impacts are the result of resource use and environmental releases to air, water, and land. Although no universal methods exist for precisely characterizing and aggregating environmental burdens, Figure 2.5 shows a partial example of an environmental profile for the automobile, focusing on energy consumption. As illustrated, impacts generally are not uniformly distributed across an automobile's life cycle. Energy consumption associated with the use phase dominates the other life cycle stages. It is important to recognize that human communities and ecosystems also are impacted by many product life cycle systems. Synergistic or antagonistic effects, however, are difficult to detect and measure.

2.3 Life Cycle Design Principles

Three main principles guide environmental improvement of product systems in life cycle design:

- Systems analysis of the product life cycle
- Multicriteria analysis of environmental, performance, cost, and legal requirements and issues
- Multistakeholder participation and cross-functional teamwork throughout design



Assumes a 1395 kg car over 120,000 mi at 24.3 mpg; production = material production + assembly. Source: Ref. 8.

Fig. 2.5 Life cycle energy consumption for automobiles.

2.3.1 Systems Analysis

Systems analysis focuses on understanding the behavior of individual components of a system and the relationships between the collection of components that constitute the entire system. Understanding the interrelationships among societal needs, industrial systems that provide goods and services, political and regulatory systems, and the ecological systems impacted by human activities is a complex challenge. Table 2.1 shows organizational hierarchies for each of these systems. A table of hierarchies can be useful for examining interactions among systems and exploring how decisions and processes at different system levels influence higher and lower levels.

Figure 2.6 can serve from the broadest perspective to investigate the industrial ecology of the automobile. At the highest level of an industrial system is the global flow of materials and energy related directly and indirectly to the automobile. At the transportation sector level, the automobile is one of several alternative modes including airplanes, buses, trains, and bicycles. A general classification would distinguish between transport of passengers and transport of goods. Intermodal transport may combine the automobile with one or more other modes. From a national energy policy perspective, for example, it would be important to compare energy consumption for alternative transportation systems. Chapter 5 provides the energy intensity of alternative modes for passenger travel.

Life cycle design focuses on the product systems level in the industrial systems hierarchy. However, understanding the contribution of product systems to higher order levels (i.e., global flows of materials and energy, economic sectors, and corporations), as well as the influence of individual subsystems (specific life cycle stages and unit operations), is crucial to improving automobiles and other complex product systems. Successfully reducing net environmental impacts from product systems while meeting societal needs requires an awareness of the complex interactions that exist among different hierarchical levels and among the various organizational categories (e.g., economic, ecological, and sociological structures).

Interconnected Product Systems

Different product systems are often linked. Although these interconnections may complicate analysis, they also offer opportunities for reducing environmental impact. For example, different product systems frequently are connected through material exchange or common processes activities. Figure 2.7 shows how the automobile (Product 1) and other product systems (Product 2) can be linked through recycling. An important objective of life cycle design is addressing how a product system fits into the larger industrial web of highly integrated activities.

TABLE 2.1. ORGANIZATIONAL HIERARCHIES IN INDUSTRIAL ECOLOGY

Political Organizations	Social Organizations	Industrial Organizations	Industrial Systems	Ecological Systems
UNEP	World human population	ISO	Global human material and energy flows	Ecosphere
USA (EPA, DOE)	Cultures	Trade	Sectors (e.g., associations and health care)	Biosphere transportation
State of Michigan (MDNR)	Communities	Corporations/ companies	Product systems	Biogeographical region
Washtenaw County	Households	Divisions	Life cycle stages	Biome landscape
City of Ann Arbor consumers	Individuals/	Product development teams	Unit	Ecosystem
Individual Voter		Individuals		Organism

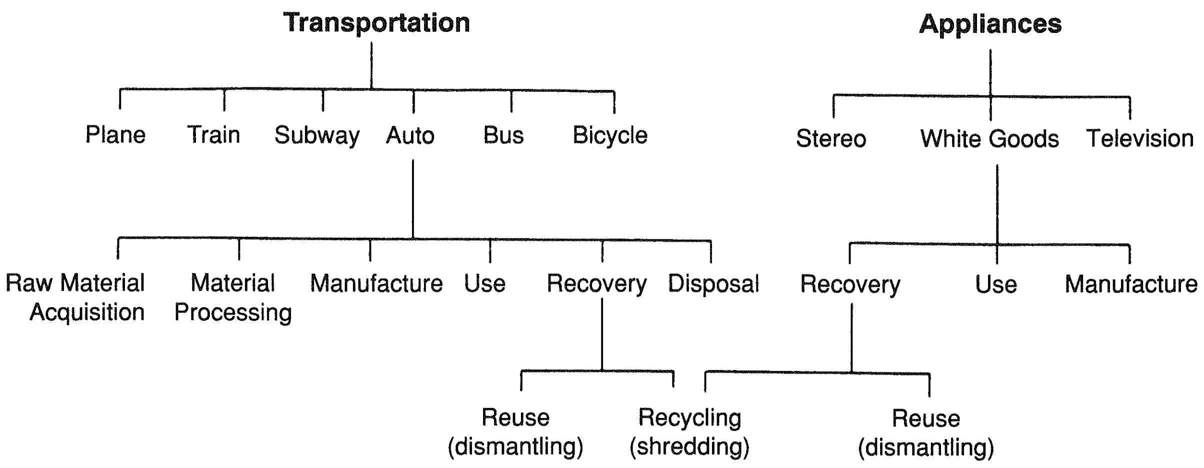


Fig. 2.6 Interconnection among industrial sectors.

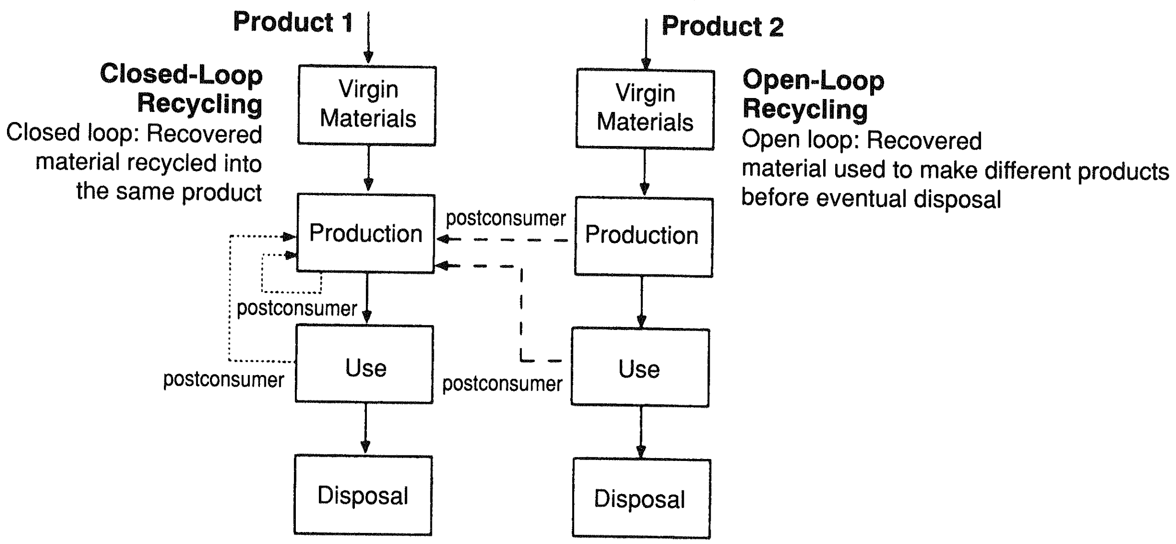


Fig. 2.7 Product systems linked through recycling.

Interlinked systems associated with the automobile exist at the sector level and the product level. At the sector level, the automobile shares the roads and highway infrastructure with buses, trucks, and sometimes bicycles. Systems are linked through recycling by the use of common process equipment and material. Equipment that shreds automotive hulks also processes white goods such as refrigerators and washing machines. Primary aluminum from aircraft fuselages may become secondary aluminum used in automotive applications such as engine blocks or manifolds. Chapter 6 covers vehicle retirement and presents other cases of material recycling.

Systems analysis also indicates the degree of connectedness between system components and processes and life cycle stages. Material selection affects the entire vehicle life cycle. Material selection determines the nature of raw materials extracted and the potential for material recovery after vehicle retirement. The processes used to mine ore, however, will have essentially no impact on other stages of an automobile life cycle.

The automobile system is simplified by organizing it into closely interconnected subsystems. Primary subsystems of the automobile include powertrain, heating and cooling, electrical, and body and chassis. Adding weight to the vehicle powertrain can have secondary effects on fuel economy by requiring a more substantial frame and braking system.[9]

2.3.2 Multicriteria Analysis

Life cycle design seeks to meet environmental objectives while best satisfying cost, performance, and legal requirements. Tools that support design and management of the automobile system include tools for specifying design requirements and analytical tools for evaluating system performance, such as life cycle assessment. These tools are discussed later in this chapter. This book focuses on environmental burdens and environmental policies and regulations associated with the automobile system. Although performance and cost are primary factors influencing design and management decisions, our study did not address these factors in detail.

2.3.3 Multistakeholder Participation

The life cycle of an automobile is managed by various stakeholders, which are represented in Table 2.2. Original equipment manufacturers (OEMs) have the greatest responsibility in representing the interests of these stakeholder groups through vehicle design and production. Many recently proposed environmental initiatives involve multistakeholder groups. Initiatives discussed in this book include the Common Sense Initiative and Partnership for a New Generation of Vehicles. Substantive information on other multistakeholder initiatives, such as the President's Council on Sustainable Development project and the EXCELL program, were not available at the time of this investigation and are not included here.

Interdisciplinary participation is key to defining requirements that reflect the diverse needs of multiple stakeholders such as suppliers, manufacturers, consumers, resource recovery and waste managers, the public, and regulators. Within corporations, successful life cycle design requires the full participation of all members of a cross-functional development team.

TABLE 2.2 EXAMPLES OF STAKEHOLDERS IN THE AUTOMOBILE LIFE CYCLE

Life Cycle Stage	Companies (Examples)	Trade and Government Organizations (Examples)
Material Acquisition		
Mining	Anaconda, Phelps Dodge	
Petroleum Drilling	Shell, Exxon	American Petroleum Institute
Materials Processing		
Refining, Smelting	Shell, Exxon	
Polymerization	Dupont, Dow	American Plastics Council
Metal Production	Alcoa, USX, Inland Steel	American Iron & Steel Institute
Manufacturing		
Suppliers	Magnum Industries, 3M	Automotive Suppliers Institute
OEMs	Chrysler, Ford, GM, Foreign	U.S. Council for Automotive Research, American Automobile Manufacturers Association, United Auto Workers
Use		
Customers		Automobile Association of America
Regulators		U.S. Environmental Protection Agency, Departments of Transportation, National Highway Safety Administration
Dealers		National Automotive Dealers Association
Service Industry		Automotive Service Association
Retirement		
Dismantling	Metal Recycling Unlimited	Automotive Recyclers of America
Shredding	Auto Shredder of Michigan	
Recycling	Huron Valley Steel	Institute of Scrap Recycling Industries
Remanufacturing		American Part Rebuilders Association
Landfill Disposal	Browning Ferris, Waste Management Inc.	Solid Waste Association of North America

2.4 Life Cycle Management

Life cycle management includes all decisions and actions taken by multiple stakeholders which ultimately determine the environmental profile and sustainability of the product system. Other uses of the term "life cycle management" have referred to a more limited domain of the life cycle.[10] Key stakeholders are users and the public, policy-makers/regulators, material and waste processors, suppliers, manufacturers, investors/shareholders, the service industry, and insurers. Each stakeholder has an important role in guiding improvement, as indicated in the following list:

Stakeholders	**Roles**
Users and Public	Advance undertanding and values through education Modify behavior and demand toward more sustainable lifestyles
Policy-makers and Regulators	Develop policies to promote sustainable economies and ecological systems Apply new regulatory instruments or modify existing regulations Apply new economic instruments or modify existing ones Research and develop more sustainable technologies
Suppliers, Manufacturers, End-of-Life Managers	Design cleaner products and processes Produce sustainable products Improve the effectiveness of environmental management systems
Investors/Shareholders	Support cleaner product system development
Service Industry	Maintain and repair products
Insurance Industry	Assess risk and cover losses

Design and management decisions made by the OEM may have the greatest influence over the life cycle environmental profile of a product system. It is useful to distinguish between environmental management by internal and external stakeholders. A major challenge for product manufacturers is responding to the diverse interests of external stakeholder groups.

The environmental management system (EMS) within a corporation is the structure of responsibilities, policies, practices, and resources for addressing environmental issues. Several voluntary EMS standards and guidelines have been developed.[11–13] Although EMS activities have emphasized proactive measures in addition to regulatory compliance, these systems traditionally address only the manufacturing domain of the corporation and not end-of-life management or material acquisition stages.[14] Common elements of most EMS guidelines include policies, goals, performance measures, information/communication management systems, and training programs. Chapter 4 discusses the EMSs of Chrysler, Ford, and GM.

2.5 Life Cycle Development Process

The product development process varies widely, depending on the type of product and company and the design management organization within a company. However, most development processes incorporate the key activities shown in Figure 2.8. For life cycle design, this process occurs within the context of sustainable development and life cycle management. Three types of development activities will be briefly described here: specification of requirements, design evaluation tools, and strategies for achieving design solutions.

2.5.1 *Specification of Requirements*

Specification of requirements is one of the most critical design functions. Requirements guide designers in translating needs and environmental objectives into successful designs. Environmental requirements should focus on minimizing natural resource consumption, energy consumption, waste generation, and human health risks as well as promoting the sustainability of ecosystems. A primary tool of life cycle design is the set of multicriteria matrices for specifying requirements shown in Figure 2.9. Other tools for guiding designers include design checklists and guidelines.

The matrices shown in Fig. 2.9 enable product development teams to study the interactions and tradeoffs among environmental, cost, performance, and legal requirements. Each matrix is organized by life cycle stages and product system components. Elements then can be described and tracked in as much detail as necessary. Requirements can include qualitative criteria and quantitative metrics.

In addition to the noncomparability of environmental impacts, noncomparability exists among environmental, cost, performance, and legal criteria.

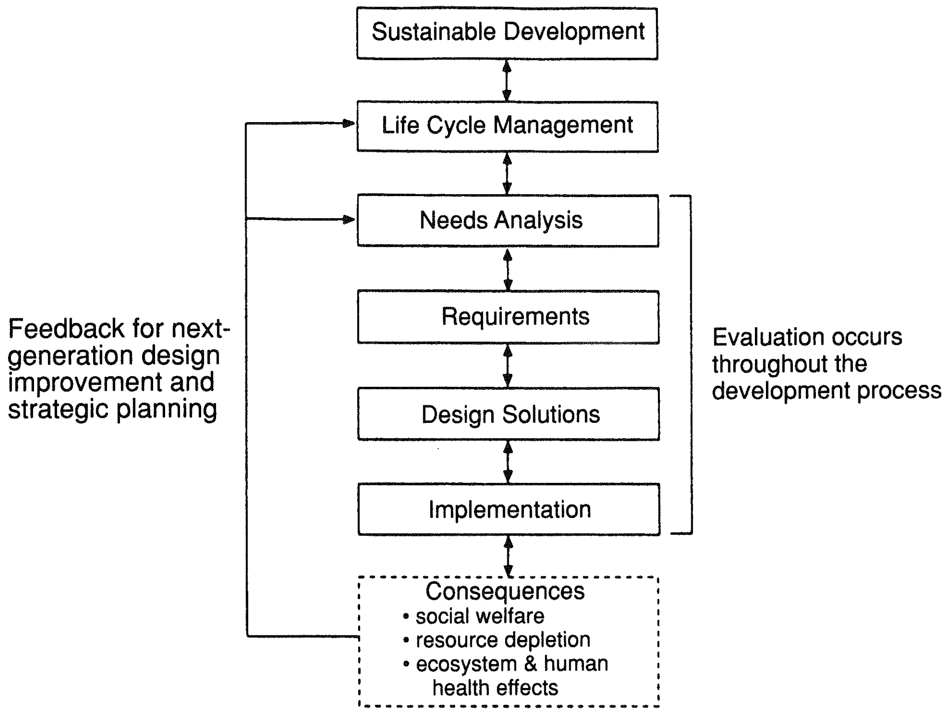


Fig. 2.8 Life cycle development process.

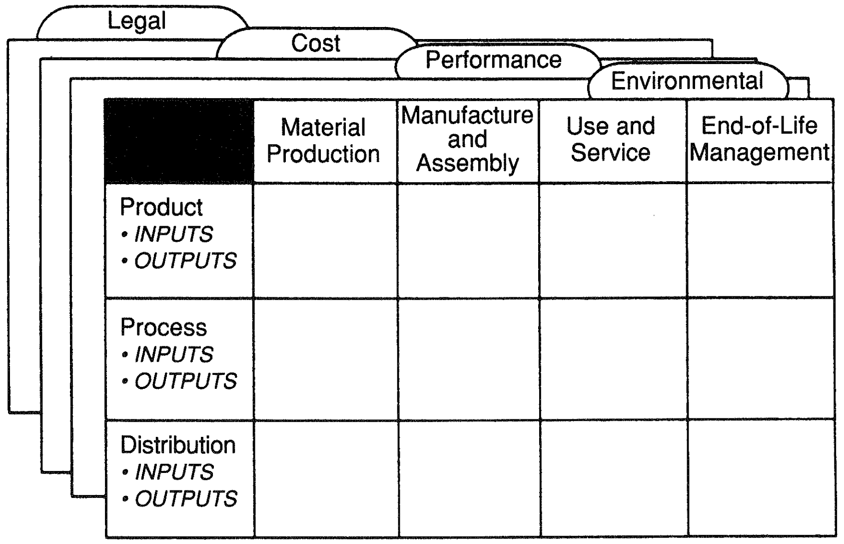


Fig. 2.9 Multicriteria requirements matrices.

Although several factors complicate the comparison of alternatives, such as different units of measurement and different degrees of uncertainty in the data and potential outcomes, product realization and management teams need a mechanism for comparing alternatives. In many cases, the optimal environmental solution may conflict with the most cost-effective choice as computed by a corporation's accounting system. In some cases, a clear option emerges, but criteria generally must be weighted to resolve conflicting requirements.

2.5.2 *Design Evaluation*

Analysis and evaluation are required throughout the product development process and during strategic planning by management. Approaches for design evaluation range from comprehensive analysis tools such as life cycle assessment (LCA) to the use of single environmental metrics. LCA tools can be broadly classified as Society of Environmental Toxicology and Chemistry (SETAC)-related methodologies,[15–17] semiquantitative matrix evaluation tools,[18–19] and other techniques such as the Environmental Priority Strategies (EPS) system.[20] For example, Graedel *et al.*[18] have developed an abridged LCA approach. The matrix scoring system developed by Graedel *et al.* is a streamlined tool that does not rely on comprehensive inventory data but rather on the experience of environmental health professionals. These established criteria can be used to screen alternative products or materials. A 5×5 matrix is organized by five life cycle stages and five environmental concerns, including materials choice, energy use, solid residues, liquid residues, and gaseous residues. Each element of the matrix receives an integer rating between 0 and 4. The advantage of this approach is that the matrix elements can be added together to determine an overall Environmentally Responsible Product Rating. The primary limitation of this method is that it requires expert judgment in scoring and weighting each matrix cell; consequently, it can be highly subjective.

The Product Ecology Project, a collaboration between European industry and academia, is another example where life cycle inventory and a valuation procedure support product development.[20] For this project, the EPS system in product design is used to evaluate the environmental impact of design alternatives using a single metric based on environmental load units. An inventory is conducted using the LCA Inventory Tool developed by Chalmers Industriteknik, and valuation is based on a willingness-to-pay model that accounts for biodiversity, human health, production, resources, and aesthetic values. This system enables the designer to easily compare alternatives, but the reliability of the outcome is heavily dependent on the valuation procedure.

If environmental requirements for the product system are well specified, design alternatives can be checked directly against these requirements. Several tools for environmental accounting and cost analysis are also emerging.[21–24] Cost analysis for product development is often the most influential tool to guide decision-making. Key issues of environmental accounting are measuring environmental costs, allocating environmental costs to specific cost centers, and internalizing environmental costs.

In principle, LCA represents the most accurate tool for design evaluation in life cycle design and Design for Environment (DFE). Many methodological problems, however, currently limit the applicability of LCA to design.[25] Costs to conduct an LCA can be prohibitive, especially to small firms, and time requirements may not be compatible with short development cycles.[26,27] Although significant progress has been made toward standardizing life cycle inventory analysis,[15–17,28] results can vary significantly.[29,30] Such discrepancies can be attributed to differences in system boundaries, rules for allocation of inputs and outputs between product systems, and data availability and quality issues.

Incommensurable data present another major challenge to LCA and other environmental analysis tools. A large, complex set of inventory data can overwhelm designers and managers, who often lack environmental training and expertise. The problem of evaluating environmental data remains inherently complicated when impacts are expressed in different measuring units (e.g., kilojoules, cancer risks, or kilograms of solid waste). Furthermore, impact assessment models vary widely in complexity and uncertainty.

Even if better assessment tools existed, LCA has inherent limitations in design and management because the complete set of life cycle environmental effects associated with a product system cannot be evaluated until a design has been specified in detail.[25] This limitation indicates the importance of requirements matrices, checklists, and design guidelines, which can be implemented during conceptual design phases.

Despite these barriers and limitations, numerous studies have applied LCA tools to automotive design and analysis (e.g., Refs. 8, 20, and 31–34). Specific topics investigated include material selection,[20,31–33] energy consumption,[8,32,33] and emissions.[34]

For life cycle design and management to be effective, environmental costs must be allocated accurately to product centers. Environmental costs are commonly treated as overhead. Methods such as activity-based costing may be useful in properly assigning product costs in many situations, resulting in improved decision-making.[35,36] Properly allocating environmental costs can be one of the most powerful motivators for addressing environmental issues in design.

Unfortunately, the current market system does not fully account for environmental costs; therefore, prices for goods and services do not reflect total costs or benefits. Thus, a design that minimizes environmental burden may appear less attractive in terms of cost than an environmentally inferior alternative.

The most significant unrealized costs in design are externalities, such as those resulting from pollution, which are borne by outside parties (society) not involved in the original transaction (between manufacturers and customers). Corporations choosing to reduce emissions and internalize the associated costs may experience a competitive disadvantage unless their competitors do so as well.[37] Despite this problem, manufacturers can benefit from pursuing design initiatives that produce tangible savings through material conservation or reduction in waste management and liability costs.

Several resources are available to identify full environmental costs.[21,22] In the U.S. Environmental Protection Agency (EPA) Pollution Prevention Benefits Manual, costs are divided into four categories: usual costs, hidden regulatory costs, liability costs, and less tangible costs. Usual costs are standard capital and operating expenses and revenues for the product system. Hidden costs represent environmental costs related to regulation (e.g., permitting, reporting, and monitoring). Costs arising from noncompliance and future liabilities for forced cleanup, personal injury, and property damage, as well as intangible costs/benefits such as effects on corporate image, are difficult to estimate. In any case, methods for evaluating and internalizing externalities are limited.

From a consumer's perspective, life cycle costing is a useful tool for making product selection decisions. In traditional use, life cycle costs consist of the initial purchase price plus operating costs for consumables (e.g., fuel, electricity, and lubricants), servicing not covered under warranty, and possible disposal costs.[38] Providing estimates of life cycle cost can be a useful marketing strategy for environmentally sound products.

The most comprehensive definition of life cycle costs is the sum of all internal and external costs associated with a product system throughout its entire life cycle.[23,39] At present, government regulation and related economic policy instruments appear to be the only effective methods of addressing environmental costs to society.

2.5.3 Design Strategies

Selecting and synthesizing design strategies for meeting the full spectrum of requirements is a major challenge of life cycle design and management. General strategies for fulfilling environmental requirements are shown in Table 2.3. An explanation of each strategy is provided in the *Life Cycle Design Guidance Manual* published by EPA. Most of these strategies reach across product system boundaries; life extension, for example, can be applied to various elements in all three product system components.

TABLE 2.3. SUMMARY OF DESIGN STRATEGIES

General Categories	Specific Strategies
Product Life Extension	Extend useful life
	Increase durability
	Ensure adaptability
	Increase reliability
	Expand service options
	Simplify maintenance
	Facilitate reparability
	Enable product remanufacture
	Accommodate product reuse
Material Life Extension	Develop recycling infrastructure
	Examine recycling pathways
	Use recyclable materials
Material Selection	Use substitute materials
	Devise reformulations
Reduced Material Intensiveness	Conserve resources
Process Management	Substitute better processes
	Increase process energy and material efficiency
	Improve process control
	Control inventory and material handling
	Plan facilities to reduce impacts
	Ensure proper treatment and disposal
Efficient Distribution	Optimize transportation systems
	Reduce packaging
	Use alternative packaging materials
Improved Management Practices	Use office materials and equipment efficiently
	Phase out high-impact products
	Choose environmentally responsible suppliers or contractors
	Encourage ecolabeling and advertise environmental claims

In most cases, a single strategy will not be best for meeting all environmental requirements. Recycling illustrates this point. Many designers, policy-makers, and consumers believe recycling is the best solution for a wide range of environmental problems. Although recycling can conserve virgin materials and divert discarded material from landfills, it also causes other impacts and thus may not always be the best way to minimize waste and conserve resources.

Single strategies are unlikely to reduce environmental burden in all life cycle stages; they are even less likely to satisfy the full set of performance, cost, and legal requirements. Appropriate strategies must satisfy the entire set of design requirements shown in Figure 2.9, thus promoting integration of environmental requirements into design. For example, essential product performance must be preserved when design teams choose a strategy for reducing environmental impacts. If performance is so degraded that the product fails in the marketplace, the benefits of environmentally responsible design are only illusory.

In most cases, successful development teams adopt a range of strategies to meet design requirements. As an example, design responses to an initiative such as extended producer responsibility[40,41] are likely to include waste reduction, reuse, recycling, and aspects of product life extension.

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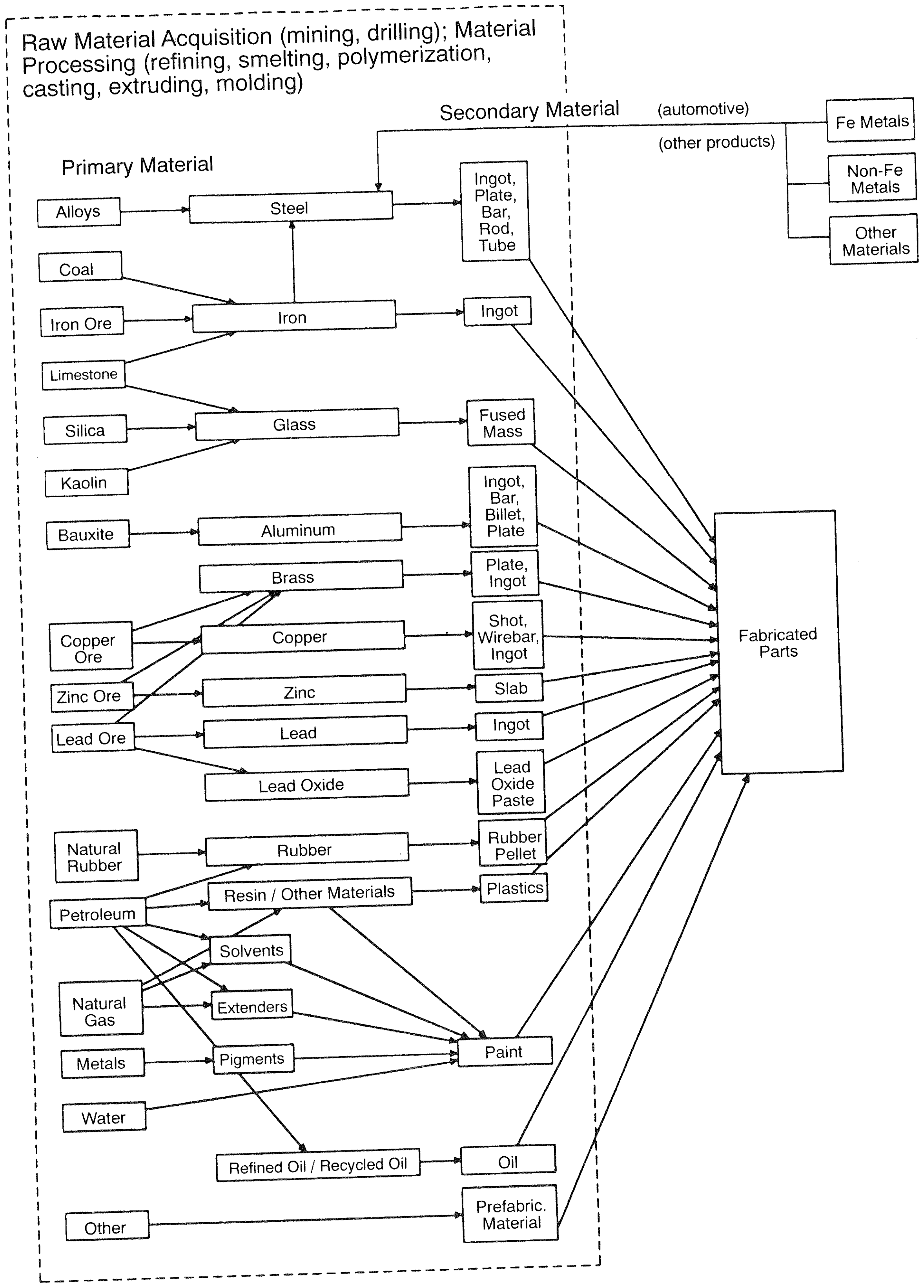
Materials Production



Chapter 3

Materials Production

The life cycle of an automobile begins with materials production, which includes resource extraction and materials processing activities. Activities such as mining of hard-rock minerals, drilling for petroleum, refining and smelting, steel-making, and polymerization processes each result in a variety of environmental burdens. Upstream consequences associated with the material inputs for a particular vehicle system are determined by material selection decisions made primarily by OEMs and their suppliers. It is useful to distinguish between product, process, and distribution material inputs according to the classification in Chapter 2. Chapter 3 addresses product materials that constitute the automobile. Material composition for a typical automobile from 1980 to 1994 is shown in Table 3.1.

In 1994, steel accounted for 54.8% of the vehicle by weight, iron 12.9%, plastics 7.7%, fluids 6.0%, aluminum 5.7%, and rubber 4.2%. Steel and aluminum are the materials used most often in load-bearing automotive applications. Plastics and composites are used exclusively in

TABLE 3.1. ESTIMATED AVERAGE MATERIAL COMPOSITION (LBS) FOR U.S.-BUILT CARS

Material	1980	1982	1984	1986	1988	1990	1992	1994
Conventional Steel (includes cold-rolled and precoated)	1737	1479	1488	1446	1337	1245	1379	1389
High-Strength Steel	175	199	214	221	228	233	247	263
Stainless Steel	27	29	29	30	31	32	42	45
Other Steels	54	46	45	47	47	53	42	43
Iron	484	452	455	447	427	398	430	408
Aluminum	130	136	137	142	150	159	174	182
Rubber	131	132	134	132	130	128	133	134
Plastics and Plastics Composites	195	203	207	216	220	222	243	246
Glass	84	86	87	87	86	83	88	89
Copper and Brass	35	39	44	43	50	46	45	42
Zinc Die Castings	20	15	17	17	20	19	16	16
Powder Metal Parts	17	18	19	20	22	23	25	27
Fluids and Lubricants	178	180	180	183	177	167	177	190
Other Materials	96	91	88	90	89	88	96	99
Total	3363	3102	3142	3118	3010	2896	3136	3171

Totals may differ from sum of columns because of rounding.
Source: Ref. 1.

non-load-bearing applications.[2] Trends indicate an increase in the use of plastics and lightweight metals. Between 1980 and 1994, the aluminum content of the automobile increased 40%; the plastic content increased 26% during the same period.

In addition to product design decisions, material selection affects process design and management for each life cycle stage. Other important material issues, including the effects of material substitution on fuel economy and recycling, will be covered in subsequent sections of this book.

Material selection is a fundamental design activity that influences environmental burdens throughout the life cycle of an automobile. It is one of the most significant decisions in designing automotive parts and components. The automotive industry uses 23 million tons of material annually to produce approximately 12 million vehicles.[2]

3.1 Environmental Burden

This section characterizes the environmental burdens resulting from materials production, which includes raw material acquisition and material processing. Data is provided for some of the key materials, and examples of different types of impact are presented.

3.1.1 Resource Use

The automotive industry is among the most resource intensive of all major industrial systems. Table 3.2 characterizes the overall material intensity of the automotive industry in 1992. Automotive industry use represents at least one-third of the overall U.S. consumption of iron, lead, platinum, and synthetic and natural rubber. Data provided in Table 3.2 include primary and secondary materials used by the automotive industry. The percentage of ferrous recycled materials that are used in the manufacture of new vehicles is given in Table 3.3.

Approximately 60 to 70% of the aluminum in new vehicles comes from recycled material.[4] Therefore, based on ferrous and aluminum material alone, the recycled content of an average 1994 car is approximately 33%.

TABLE 3.2. MATERIAL USE BY THE AUTOMOTIVE INDUSTRY, 1992[a]

Material	Automotive Consumption	Total U.S. Consumption	Automotive Percentage
Aluminum (1000 lbs)	2,844,000	15,011,000	18.9
Copper and Cu Alloy (1000 lb)	660,000	6,593,000	10.0
Cotton (480-lb bales)	22,000	10,010,000	0.2
Gray Iron (tons)	2,295,000	6,473,000	35.5
Ductile Iron (tons)	942,000	3,116,000	30.2
Malleable Iron (tons)	167,000	280,000	59.6
Total Iron (tons)	3,404,000	9,869,000	34.5
Lead (metric tons)	864,628	1,244,000	69.5
Plastic (1000 lb)	2,197,000	67,675,000	3.2
Platinum (troy oz)	847,589	2,047,935	41.4
Natural Rubber (metric tons)	680,406	910,212	74.7
Synthetic Rubber (metric tons)	1,129,342	1,946,920	58.0
Alloy Steel (tons)	489,000	4,101,000	11.9
Stainless Steel (tons)	250,000	1,514,000	16.5
Total Steel (tons)	11,092,000	82,241,000	13.5
Zinc (tons)	268,000	1,165,000	23.0

a Includes use of materials for automobiles, trucks, buses, and replacement parts. These data include use of secondary materials, in addition to virgin or primary materials.
Source: Ref. 1.

TABLE 3.3. FERROUS RECYCLED CONTENT OF AVERAGE NEW VEHICLE

Ferrous Material	Average Recycled Content[a]	Pounds per Car	Material Content per Car
Sheet, Strip and Bar	28.5%	1388.5	43.8
High and Medium Strength	28.5%	133.0	4.2
High and Medium Strength	100.0%	130.0	4.1
Stainless	100.0%	45.0	1.4
Other Steels	28.5%	42.5	1.3
Iron	75.0%	408.0	12.9
Total Ferrous	43.2%	2147.0	67.7%
Total Car		3171.0	

a Recycled content includes pre- and postconsumer.
Source: Ref. 3.

The source of secondary material used to manufacture new vehicles is more difficult to trace. For example, steel recovered from scrapped vehicles contains copper impurities, which limit its use in the production of high grades of steel. Copper specifications for steel range from 0.05% for deep-drawing steels to 0.5% for rebar.[5] Copper impurities can cause defects in casting, rolling, and welding. The copper content of automobile shredder scrap is 0.25 to 0.3%; however, it has been reported that ferrous scrap generally has an average copper content of approximately 0.35%.[5] Steel producers meet copper specifications by dilution and scrap blending, which can be used to decrease the high copper content of a certain scrap feedstock.

Ginley[6] indicates that materials recovered from the dismantling process, such as batteries, bumpers, radiators, and aluminum engine blocks, are pure enough to be directly recycled back into the automobile material processing stage. This accounts for approximately 8.6% of all material inputs for fabricating a 1994 car.[6]

Some postconsumer plastic from the automobile and other sources also is beginning to be recycled into new vehicles, as shown in Table 3.4.

3.1.2 Materials Acquisition

The acquisition and processing of virgin resources that serve as inputs for automotive materials represent a significant environmental impact that is unique to the materials production stage of the automobile life cycle. The consumption of mineral resources by the automotive industry affects resource quality and environmental quality. The depletion of nonrenewable resource stocks limits future generations' access to these valuable materials. Resource optimists[10–12] suggest that human ingenuity and technological advancements make issues of resource quality irrelevant. Hall *et al.*[13] summarize the view held by many optimists as follows:

> ...resource depletion creates its own remedy. Society avoids potentially adverse effects of declining resource quality by developing resource-augmenting technologies and by substituting more abundant resources for scarcer ones. Price increases of the scarcer material provide the stimulus for both these changes.

Conversely, resource pessimists have argued that society will exhaust nonrenewable resources necessary for industrial activity.[14] A large-scale computer model developed by Forrester was constructed to simulate future outcomes of the world economy. Resource consumption, population, food supply, and industrial output were modeled. The following conclusions were drawn by Meadows *et al.*, who applied the Forrester model[15]:

> If the present growth trends in world population, industrialization, pollution, food production, and resource depletion continue unchanged, the limits to growth on this planet will be reached sometime within the next 100 years. The most probable result will be a sudden and uncontrollable decline in both population and industrial capacity. It is possible to alter these

growth trends and to establish a condition of ecological and economic stability that is sustainable far into the future. The state of global equilibrium could be designed so that the basic material needs of each person on earth are satisfied and each person has an equal opportunity to realize his or her individual human potential.

TABLE 3.4. USE OF RECYCLED PLASTICS AND RUBBER IN AUTOMOBILE PARTS

Source of Recycled Material	Parts with Postconsumer Recycled Content
Acrylonitrile Butadiene Styrene (ABS)	Painted light truck grills Car and truck lamps
Polyethylene Terephthalate (PET) Soda Bottles	Grill opening reinforcements Luggage racks Door padding Headliner cores, sound deadeners Headlamp support bracket Door handle escutcheons Truck carpeting Window guides and sashes Seat cover trim pads
Polycarbonate (compact discs and water bottles)	Steering column closeout Sunroof cover retainers
Polyvinylchloride (PVC)	Fender to cowl barrier Door watershield Rear quarter barrier Floormats Front assembly wheel house
Polypropylene, Auto Battery Cases	Battery trays
Polypropylene (20% talc filled)	Air conditioner heater core plenum housings
Tires	Brake pedal pads
Battery Housings	Splash shields
Bumpers	Tail lamps (prior to 1996 models)

Source: Refs. 7–9.

Some physical scientists argue that geological and energetic constraints ultimately determine the availability of nonrenewable resources.[16,17] To recover minerals occurring at their crustal abundance requires large investments of energy to break down the crystalline structure of host rock.

Both sides offer compelling points that should be considered when developing resource policy.

At present, annual rates of material consumption sharply contrast the extremely long time scales associated with the formation of mineral resources through various geochemical processes. Extractive resources are classified as either renewable or depletable, depending on whether they regenerate themselves naturally within an economically viable time frame. Oil, gas, copper, and bauxite are depletable resources; timber and fisheries are renewable if managed properly. The actual occurrence of a mineral resource within the earth's crust composes the *resource endowment*. *Current reserves* are those reserves that can be profitably extracted at current prices with current technologies. *Potential reserves* are mineral resources that may be extracted at some future date because of a technological improvement or an increase in prices.[18]

The mineralogical threshold represents the minimum natural conditions that permit formation of separate particles of specific minerals that can be recovered by current methods.[17] Below this level, elements become dispersed in the crystalline structure of other minerals found in the ordinary rock that composes the earth's crust.[13] The concentration of an element in the earth's crust is referred to as the crustal abundance or Clark concentration. Table 3.5 shows geochemically abundant elements and geochemically scarce elements. Elements that have a crustal concentration less than 0.01% are considered scarce.

TABLE 3.5. ABUNDANCE OF SOME ELEMENTS IN EARTH'S CRUST

Abundant Elements		Scarce Elements	
Element	Percent by Weight of Earth's Crust	Element	Percent by Weight of Earth's Crust
Oxygen	46.60	Copper	0.007
Silicon	27.27	Zinc	0.008
Aluminum	8.13	Lead	0.0016
Iron	5.00	Silver	0.00001
Calcium	3.63		0.0000005
Sodium	2.83		
Potassium	2.59		
Magnesium	2.09		
Titanium	0.44		
Hydrogen	0.14		

Source: Ref. 20.

The practical availability of minerals is controlled by geologic, engineering, environmental, and economic factors.[19] For example, geologic factors that influence the economic potential of a resource are grade of the ore, depth of burial, and mode of occurrence of the mineral deposits.

Recycling and reuse of a resource will lengthen the useful life of a resource stock, but no material can be recycled completely because of process inefficiencies. Thus, the use of natural resources is an issue of intergenerational equity. Resources consumed by the present generation are made unavailable to subsequent generations. Material selection decisions made by OEMs today will affect the supply and availability of materials incorporated into future fleets of automobiles. Earlier estimates of resource depletion predicted exhaustion of certain materials such as aluminum. Today, aluminum reserves are considered abundant relative to copper and zinc, which are geochemically scarce metals concentrated in a limited number of deposits. Table 3.6 shows estimates for the availability of world minerals using current levels of reserves and mineral production.

The point in time at which a resource stock will be exhausted is difficult to predict because of uncertainties such as technological improvements, product and input substitutability, and rates of extraction and recycling.

Petroleum and natural gas are nonrenewable feedstocks for the plastics industry. The exact longevity of petroleum and natural gas reserves is highly controversial. Table 3.7 provides estimates for years of energy supplies based on projected rates of consumption.

TABLE 3.6. WORLD MINERAL RESERVES AT 1992 ANNUAL PRODUCTION

Reserves/ 1992 Production	Minerals
100 + Years	Soda ash, rare earths, yttrium, magnesium, sodium sulfate, diatomite, lithium, iodine, coal, potash, columbium, bauxite, rutile, platinum group, iron ore, vanadium, boron, chromium
50–100 Years	Cobalt, vermiculite, phosphate, rhenium, antimony, tantalum, ilmenite, natural gas, tungsten, zirconium, nickel
25–50 Years	Molybdenum, oil, selenium, fluorspar, copper, uranium, bismuth, manganese, graphite, barite, strontium, peat, tin, cadmium
10–25 Years	Thallium, sulfur, mercury, gold, arsenic, lead, zinc, diamond, silver, indium

Minerals are defined broadly here to include all nonbiological resources.
Source: Ref. 19.

The relatively limited supply of some energy feedstocks poses important questions for the automobile industry. Is it wiser to conserve resources to produce plastics or to consume petroleum as a fuel source?

3.1.3 Mining and Drilling Impacts

Mining operations can be categorized as surface or underground mining. In addition to resource depletion, mining

TABLE 3.7. 1988 WORLD ENERGY CONSUMPTION AND RESERVES

Resource	% of Total Consumption	Annual Use (Quads)	Reserves[a] (Quads)	Years of Supply at 1988 Rates
Oil	38%	121	7000	60
Coal	30%	96	150,000	1,500
Natural Gas	20%	64	8,000	120
Hydroelectric	7%	22		
Nuclear	5%	17		

[a] Economically recoverable; includes known and estimated undiscovered reserves. Undiscovered coal is estimated at ten times known reserves; undiscovered oil and gas are estimated at less than half known reserves.
Source: Ref. 21.

activities can result in significant ecological degradation. Mining wastes can constitute a significant fraction of the total solid waste produced during the automobile's life cycle. Table 3.8 shows waste generation from the mining of metallic ores. Waste materials are overburden and nonmetallic mineral aggregate called gangue.

TABLE 3.8. MATERIAL HANDLED IN U.S. MINES, 1993

	Total Surface and Underground (1000 metric tons)		
Metals	**Crude Ore**	**Waste**	**Total**
Copper	469,186	237,811	706,997
Gold	248,414	778,867	1,027,281
Iron	181,297	102,771	284,068
Lead	4,008	337	4,344
Nickel	355	178	533
Zinc	5,942	355	6,298
Other	45,883	19,270	65,603
Total	955,085	1,140,039	2,095,124

Source: Ref. 22.

Excavation creates dramatic degradation of a landscape, which results in habitat degradation and loss. In the United States, mines occupy approximately 3700 km^2 which is 0.26% of the nation's land area.[23] By comparison, airports and railroads each occupy 2500 km^2; highways cover 13,500 km^2. It is estimated that 60% of the disturbed mining area is used for excavation; the remaining 40% is used for disposal of overburden and other solid wastes.[19] Although the law currently requires reclamation practices for active mines, many mines abandoned prior to the law remain unrestored.

Air pollution from mining operations occurs in the form of airborne dust and emissions from mining equipment.

Mining also creates waterborne wastes such as acids, heavy metals, and other toxic substances. Water and soil quality are adversely affected through acid mine drainage, point source runoff into streams and groundwater, erosion, and sediment loading in streams and lakes. Mine drainage is often sufficiently acidic to lower the pH of nearby surface waters to a level toxic to aquatic life, particularly in the Eastern United States. Drainage from thousands of active and inactive coal mines in Appalachia has polluted approximately 10,500 miles of streams in the Eastern United States.[24]

This copper mine in Butte, Montana, demonstrates the potential severity of mining impacts[25]:

> The Berkeley Pit is a large abandoned open pit mine in Butte, MT. Since 1982 it has been filling with water; the level is currently over 213 m (700 ft) deep. At the present rate of inflow, the pit water level will rise to the low point in the rim by the year 2011. Before that time, around 1997, water rise will reach exposed alluvium in the pit walls, creating a threat to groundwater quality in the valley south of the pit. In terms of contained volume of water and quantity of metal pollutants, the Berkeley Pit is unmatched by any acid-producing mine in the United States and possibly the world. Prior to 1983, Butte had produced over 20 billion lb of copper, 4.9 billion lb of zinc, 3.7 billion lb of manganese, 850 million lb of lead, 750 oz of silver, and 2.9 million oz of gold.

Minerals are widely distributed geographically. Energy and emissions associated with transportation of minerals to processing plants should be considered. For example, virtually all high-grade bauxite is imported to the United States for the production of aluminum from tropical and subtropical regions. Australia, Jamaica, Guinea, and Brazil are major suppliers of bauxite and/or alumina to the United States.

Drilling is an important process for evaluating deposits of oil, natural gas, and minerals. Two main environmental problems of oil and gas extraction are the escape of underground fluids and land subsidence.[19]

3.1.4 Material Processing

Material processing refers to the various processes that transform virgin ores into metals and convert petroleum and natural gas into polymeric resins.

Emissions/Wastes

The first step after mining in the production of metal such as copper, chromium, iron, lead, tin, and zinc from ore is concentration or beneficiation. In this process, the ore is concentrated and the waste minerals (gangue) that are rejected are referred to as tailings. Crushing and grinding processes separate grains of ore from the gangue; this separation often is accomplished by froth flotation. In the next process, smelting, ore is reduced into its metallic state. For some ores such as aluminum, concentrates are not produced and metal is recovered directly.[19] Solid wastes and air and water emissions related to the production of aluminum, steel, copper, zinc, magnesium, and titanium are summarized by Yoshiki-Gravelsins *et al.*[26]

Steel

Steel is produced from iron ore, limestone, and coal. Two methods of steel production, the basic oxygen furnace (BOF) and electric arc furnace (EAF) methods, are used in the United States today. The open hearth production process, discontinued in the United States because of onerous energy requirements for heating, remains in use in many developing countries.[27]

The production of iron for the BOF method begins with the conversion of 65% iron ore into pig iron containing 94.3% iron.[19] Ore pellets are fed into a blast furnace and reduced to iron using coke, which is produced from coal. Impurities react with limestone to form slag. The steel-making process then occurs within a BOF by blowing oxygen through a charge of molten pig iron and iron scrap (30%). The EAF method uses only steel and iron scrap and does not require molten iron or coke.

Environmental burdens from steel-making include dust, gases, and slag. Most of the slag is recovered and sold as construction aggregate. Coke ovens may emit CO, organic fumes, and some particulates that pose significant cancer risks to nearby communities. Gaseous emissions produced in the blast furnace method include CO_2, SO_2, nitrogen oxides, and particulates. Emissions from electric arc furnaces are enriched enough in heavy metals to pose health problems. Today, almost all particulate emissions from combustion processes are successfully captured by filtered enclosure technologies.

Aluminum

Primary aluminum is produced from bauxite in a two-step process that refines alumina and reduces alumina to aluminum metal. In the first step, referred to as the Bayer process, caustic soda is used to leach alumina from bauxite. Production of aluminum from alumina is done primarily through the well-established Hall-Heroult electrolytic reduction process. This process first dissolves and combines alumina with molten cryolite and other fluorides. The molten mixture then is reduced to aluminum using an electric current.

Environmental burdens related to aluminum production include red mud from the Bayer process (approximately 1.8 tons are generated per 1.9 tons of Al_2O_3, 54% Al).[19] Red mud contains water and small amounts of heavy metals, insoluble minerals, and organic compounds. Other solid wastes resulting from smelting and finishing in aluminum production include spent potlinings containing fluoride and cyanide, cast-house dust, pot sludges, furnace skimmings, and drosses. The processing of aluminum scrap also can generate substantial impurities, or skims.

Aluminum production contributes to gaseous emissions through the use of electricity for smelting and refining. Particulate emissions associated with production consist of alumina dust, carbon dust, and particles of fluoride compounds.

Gas emissions include HF, CF_4 and other fluoride-bearing gases, CO_2, CO, and SO_2. Significant amounts of fluorocarbons are emitted at rates of 1.5 to 2.5 kg per ton of aluminum in the Hall-Heroult process. These fluorocarbons have a global-warming potential of approximately 1000 relative to CO_2 and could account for as much as 1.7% of human greenhouse gas releases.[28]

The root cause of CF_4 emissions has been identified as the frequency and duration of process upsets called anode effects.[29] Progress is being made in reducing such emissions. For example, one Alcoa smelter reduced CF_4 emissions from 1.1 kg per ton of aluminum in 1990 to 0.1 kg per ton in 1994.[29]

Large quantities of wastewater are also generated during aluminum production. These effluents are treated and then recycled. Sludges and residues containing heavy metals and organics are collected and landfilled.

Plastics/Composites

During refining, crude oil is distilled into a series of fractions, each of which is a complex mixture of hydrocarbons. Major fractions from refining include liquefied refinery gas, finished gasoline, jet fuel, fuel oil, petrochemical feedstocks, petroleum coke, asphalt/road oils, still gas, lubricants, waxes, and kerosene. Refining also removes impurities such as sulfur, salts (brine), nitrogen, oxygen, and trace metals.

The American Petroleum Institute (API) reported 5.5 M tons of total residuals from refineries in 1993. Most of the residuals from refining are spent caustics used to absorb chemicals such as phenol. The API estimates that 97% of Toxic Release Inventory (TRI) chemicals generated by refineries are recycled, treated, or burned as fuel. The majority of the remaining 3% is released to the air or injected underground. In 1993, 63% of refinery TRI releases were recycled, 19% were burned as fuel, 15% were treated, and 3% were released to the environment. Of the releases, 67% were emitted to air and 20% were injected underground.[30]

Air emissions from refining are a combination of point source emissions exiting stacks, flares, valves, flanges, and building ventilation systems. Ammonia, created by the removal of nitrogen from crude oil, is the largest TRI release by volume and is released primarily by underground injection. Other TRI releases include olefins, such as ethylene and propylene, and aromatics such as benzene and toluene, created when crude oil is refined.

Petroleum spills from transport tankers, barges, and pipelines are the largest source of emissions to water resulting from refining. Most spills occur in inland waterways—rivers, lakes, and bays.[30] Trends since 1990 include an increase in the number of small spills and a decrease in large spills.

Major automotive resins derived from petroleum and/or natural gas include nylon, polyacetal, acrylonitrile butadiene styrene (ABS), polyurethane, polyethylene, polycarbonate, acrylic, polypropylene, polyvinyl chloride, and polyester thermosets (sheet molding compound—SMC). Environmental impacts associated with the production of these resins from petroleum and natural gas feedstocks vary widely, depending on the resin. However, this study did not address the characterization of these impacts.

Energy

Energy consumption for materials production has been reported in numerous studies.[26,31,32] The significant degree of variation in these data reflect differences in the system under investigation as well as methodological differences. For example, differences in technology and equipment for mineral processing and boundary conditions can account for much of the variation. Table 3.9 shows the relative energy intensity of major materials from the most recently published comprehensive source. The ratio of secondary to primary energy requirements for various materials is given also. Some of these data can be corroborated by other recent sources; other data conflict, especially with old studies.

Energy consumption for the production of primary metals is particularly high for lightweight materials such as titanium, magnesium, and aluminum. This poses a tradeoff between material production energy and use phase energy. The secondary production of many materials consumes significantly less energy compared to primary production. Energy savings from recycling are particularly significant for aluminum and magnesium.

TABLE 3.9. AUTOMOTIVE MATERIALS PRODUCTION ENERGY

	MJ/kg		
Material	Primary	Secondary	Second/ Primary
Metals			
Al-Cast	189.2	26.0	0.14
Al-Wrought	196.1	26.7	0.14
Cu and Brass	99.9	45.0	0.45
Iron	34.0	24.0	0.71
Mg-Cast	284.2	27.2	0.10
Pb	41.1	8.0	0.19
Steel	40.1	18.2	0.45
Zn	53.0	15.9	0.30
Nonmetals			
ABS	110.8	51.4	0.46
Antifreeze	75.9		
Automatic Transmission, Brake, Steering Fluids	52.1		
Glass	30.0	13.0	0.43
Motor Oil	60.2		
Nylon	120.2	32.1	0.27
PC	158.5	48.1	0.30
PE	98.1	56.0	0.57
Polyesters	95.8	50.0	0.52
PP and Family	74.2	42.3	0.57
PU	72.1	44.6	0.62
PVC	65.4	29.3	0.45
Rubber	67.6	43.6	0.65
SMA	101.7	43.5	0.43
SMC	53.7	50.4	0.94
Thermoset - Fiber Reinforced Polyester (TS-FRP)	66.5	40.0	0.60
Phenolic	43.2	24.9	0.58
Sintered Glass	48.0		

Data were converted from Btu/lb to MJ/kg.
Source: Ref. 31.

The distribution of energy consumption among various metal production processes is given in Table 3.10.

3.2 Public Policy and Legislation

Many policies and regulations that affect the automobile in the production and use phases of the life cycle, such as CAFE standards, gasoline taxes, the Clean Air Act, and speed limits, are quite transparent and palpable to industry management and consumers. However, many other federal policies and regulations affecting the selection, processing, conversion, and distribution of materials for automotive production receive less attention. These policies and regulations address environmental burdens that result from the extraction and processing of raw materials, use of materials, disposal of residuals, and other industrial processes involved in the production of automotive materials. In addition, regulations cover other societal concerns such as national security and the establishment of strategic mineral reserves.

The principal federal regulations affecting materials acquisition and processing are the General Mining Law of 1872, the Surface Mining Control and Reclamation Act (SMCRA) of 1977, the Clean Water Act (CWA), the Clean Air Act (CAA), and the Resource Conservation and Recovery Act (RCRA). These regulations influence and possibly constrain material selection at the OEM level by affecting the prices and availability of materials to Tier 1 and Tier 2 suppliers. Tier 1 suppliers deliver directly to OEMs; Tier 2 suppliers deliver to Tier 1 suppliers.

The mining of hard-rock minerals such as gold, zinc, silver, copper, platinum, lead, and iron ore is governed by the General Mining Law of 1872, which has changed little since its enactment. Under the General Mining Law, mining companies may extract minerals from U.S. Forest Service and Bureau of Land Management lands through a patent of their mining claim. A patent is effectively a title to land and minerals for a nominal fee ($2.50 to $5 per acre), an annual claim investment of $225, and proof of a legitimate mineral deposit. Purchasing land and then selling it is permitted and is done frequently for considerable profit.

No royalties presently are paid on the value of extracted hard-rock minerals, nor are mining companies required to restore lands degraded as a result of mining activities. Because mining activities are covered under the General Mining Law, mining activities are exempt from RCRA, the principal federal law regulating hazardous waste disposal.

Many fiscally conservative legislators, environmental groups, public interest groups, and citizens agree that the General Mining Law fails to give taxpayers an adequate return on the use of public lands and is environmentally irresponsible. The General Accounting Office estimates that, in 1988, the federal government received only $4500 from 20 claims patented under the General Mining Law which transferred title to land valued between $14 M and $47 M. The environmental impacts of hard-rock mining also affect federal fiscal health. *Congressional Digest* estimates the federal government will pay an estimated $72 M to clean up 52 hazardous waste sites that have resulted from highly toxic mining methods.

Various reform efforts and bills have attempted to establish royalty fees on hard-rock minerals and federal reclamation requirements for miners. Other reforms have attempted to initiate claim fees, eliminate the patent system, and create a leasing system to finance an Abandoned Mine Reclamation Fund. To date, reform efforts have met intense resistance in Congress, especially from Western legislators who

TABLE 3.10. ENERGY CONSUMPTION IN PRODUCTION OF VARIOUS METALS (kWh/ton)

	Aluminum	Steel	Copper	Zinc	Magnesium	Titanium
Mining	1,668	1,711	6,500	139	0	NEA
Ore Preparation	8,507	922	10,920	1,101	NEA	NEA
Smelting	35,384	6,055	26,520	17,560	103,000	113,000
Casting and Finishing	4,937	2,452	5,970	1,492	NEA	NEA

NEA - No estimate available.
Source: Ref. 26.

have a significant mining presence in their states and from industry.

The SMCRA of 1977 addresses the environmental impacts of coal mining activity by establishing a coal tax to fund the reclamation of abandoned coal strip mines and a bond system that would require and guarantee reclamation of new mines if the mine permittee declared bankruptcy or avoided compliance. The Act created the Office of Surface Mining Reclamation and Enforcement (OSM) to oversee all coal extraction and to enforce citizens' complaints for noncompliance or nonenforcement. OSM's enforcement of SMCRA has been ineffective—OSM predicts that by the year 2000, only 5 to 10 percent of mines abandoned before 1977 will be reclaimed using funds generated by the coal tax. Approximately 17,000 of 24,000 surface and deep mines, refuse piles, and prep plants that opened after 1977 have been reclaimed; however, many are denuded lands inappropriate for wildlife or recreational uses.[33]

Some strip mining operations have evaded environmental enforcement by establishing shell companies to conduct mining operations and then declaring shell bankruptcy when treatment of acid drainage and other environmental remediation of the strip mine site is required. Mining states such as West Virginia have primacy with respect to reclamation enforcement. The OSM acts only when these states fail to enforce SMCRA, but the Agency has issued fewer than 25 citations in mining states on average and has eliminated many SMCRA regulations that have met opposition from industry.[33] Environmental groups are lobbying for stronger enforcement of SMCRA regulations.

Airborne emissions, wastewater, and solid wastes produced in the acquisition and processing stages of non-hard-rock minerals are regulated by the CWA, the CAA, and RCRA. These statutes are administered by EPA.

Title V of the CAA includes the issuance of operating permits to mining and other industrial facilities which are designed to prevent significant environmental deterioration. New rules regarding compliance assurance monitoring are expected to be promulgated by July 1997. These rules will provide the framework for operators to monitor air pollution control practices and to ensure that control technologies are functioning as designed.

Currently, the federal Endangered Species Act (ESA) is the only legislation that addresses the private use of natural habitats and ecosystems. The ESA limits any use of private property that may cause or contribute to the extinction of populations of flora and fauna listed as threatened or endangered under the ESA. The ESA restricts mining and extraction activities that may affect endangered species and the habitats in which they reside.

3.2.1 Resource Depletion

Because material selection is driven by cost and performance metrics, the supply and availability of natural resources and raw materials directly influence design decisions at the OEM level. Tier 1 and Tier 2 suppliers to the Big Three are generally "pricetakers" in the automotive materials markets; their (individual) demand will not influence world prices of commodities such as bauxite, petroleum, natural gas, iron, and steel. On the other hand, world prices do influence decisions among competing materials in automotive applications. Materials and processing costs are the most important factors in the automotive material selection process.[34]

However, the cost of extracting each additional unit of ore, known as the marginal cost, increases over time for many minerals because easily accessible, higher grade ores are exploited first. Table 3.11 shows the increase in energy inputs per pound of extracted copper as the grade of ore declines.

Government policies influence how renewable and depletable resources are allocated. An efficient allocation of depletable resources spreads stocks equitably among generations and promotes a smooth transition to renewable sources. Policies should address the environmental externalities that result from resource consumption. If the price of a renewable resource does not reflect the full costs borne by society because of environmental damage caused by the extraction, use, and disposal of that resource, government intervention may be justified. Current public policies addressing resource extraction in the United States, such as the General Mining Law, the SMCRA, and tax policies affecting extractive industries, do little to internalize the environmental costs of mining to the mining industry. The U.S. tax code contains provisions exempting extractive industries from taxes on capital gains or profits resulting from the sale of reserves. These provisions are referred to as the depletion allowance; they effectively subsidize the extraction of certain minerals and fuels. In 1972, this subsidy was estimated at $3.5 B.[14]

TABLE 3.11. ENERGY USED TO MINE AND PROCESS COPPER ORE

Grade, % Cu	0.70	0.10	0.01
	Energy Used (Btu/lb of Copper)		
Mining plus Concentration	33,040	231,280	2,312,800
Smelting and Refining	20,000	20,000	20,000
Total		251,280	2,332,800
Equivalent Thermal Energy in Bituminous Coal (lb of coal)	4.1	19.3	180

In this instance, copper is present as the mineral chalcopyrite ($CuFeS_2$).
Source: Ref. 13.

The impetus for reform of these policies will most likely come from environmental and public interest groups but will meet continued resistance from well-established Congressional constituencies.

3.3 Design Initiatives and Management Opportunities

Opportunities for environmental improvement exist during the material production stage for each automotive material. Material acquisition and processing industries have the primary responsibility for reducing the burdens in producing rolled steel, aluminum ingot, plastic resins, and other materials. A detailed assessment of improvement strategies, however, is outside the focus of this investigation. Technological improvements are ultimately limited only by geologic constraints which include factors such as ore grade and thermodynamics which determines the free energies for reactions. Material selection is a fundamental design activity that determines the potential of a candidate material to meet specific application goals that are required for various part and component systems and subsystems in an automobile. Because material selection affects the entire vehicle life cycle, systems analysis tools are essential in achieving aggregate reductions in environmental burdens. Consequently, this topic will be covered in Chapter 7 which discusses systems analysis.

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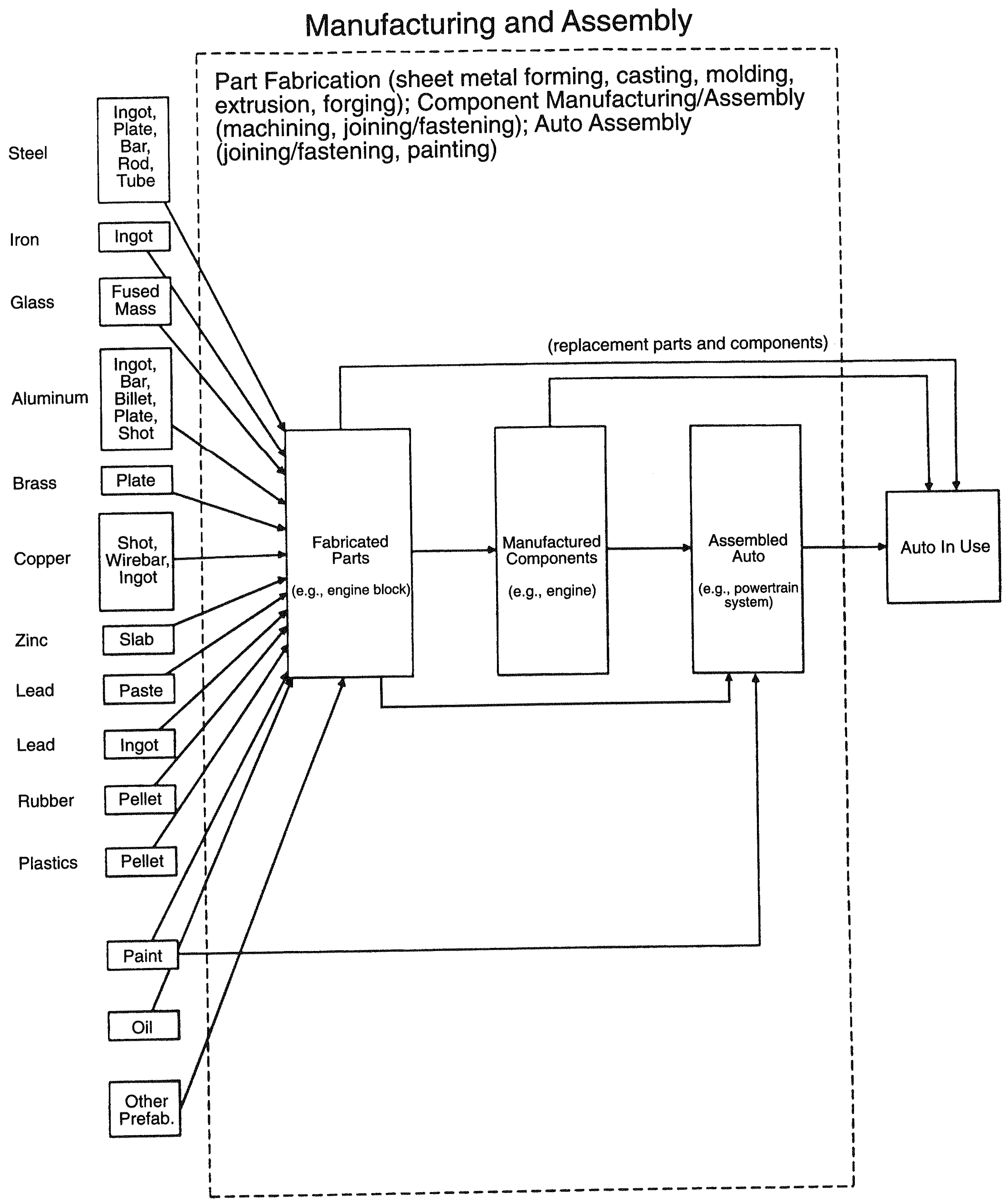

Chapter 4

Manufacturing and Assembly

Automobile manufacturing and assembly represents a complex chain of processes controlled by a network of suppliers and the original equipment manufacturers (OEMs). The OEM is primarily responsible for the environmental profile of a vehicle through its design and development. In addition, OEMs and their suppliers share direct responsibility for environmental management of the manufacturing and assembly stage of the life cycle. The OEM manages a diverse set of processes including stamping, painting, molding, welding, casting, and various assembly operations, each posing a unique set of environmental burdens.

The OEMs also outsource many production activities to suppliers. GM outsources approximately 40%, Ford about 50%, and Chrysler, which is the least vertically integrated, outsources about 60%.

The manufacturing stage of the automobile life cycle starts with the fabrication of product materials into automotive parts and components. Organization of the manufacturing stage into product system components as defined in Chapter 2 can be helpful in investigating material flows related to the approximately 20,000 parts of the automobile. Product component inputs consist of steel, aluminum, plastic, rubber, glass, and other materials that constitute the automobile. Manufacturing facilities, equipment, energy, solvents that are used as cleaners and degreasers, and lubricants for presses and molding equipment are examples of process component inputs. The distribution component is responsible for the transfer of product materials between the materials production and manufacturing stages.

4.1 Environmental Burden

Environmental burdens for automobile manufacturing are distributed between suppliers and OEMs. Suppliers in this stage, automobile manufacturing, include a wide range of parts and components fabricators. The automotive supply base is very large, which makes it difficult to aggregate data on environmental burdens and impacts. The American Automobile Manufacturers Association (AAMA) recently invited 21,000 North American suppliers to a workshop on pollution prevention (note that some of those invited were material processors).

Some suppliers are small operations that do not meet Toxic Release Inventory (TRI) reporting requirements, which are described in the next section. Because these small businesses may be exempt from TRI reporting and do not have the resources to track waste and emissions, this analysis will focus on OEMs.

4.1.1 Waste and Emissions

Waste and emissions are classified as hazardous/nonhazardous or regulated/nonregulated. Sources of publicly available data include the TRI and the OEMs' environmental reports.

TRI requirements, which were established under the Emergency Planning and Community Right-To-Know Act of 1986, contain specific toxic chemical release and transfer information from manufacturing facilities throughout the United States. Facilities that meet certain threshold requirements are required to report annually to EPA releases and transfers of listed toxic chemicals. More than 300 chemicals and 20 chemical categories were included in the 1992 list. Manufacturing facilities that have 10 or more full-time employees and that manufacture or process 25,000 lbs or otherwise use 10,000 lbs of a listed chemical are required to report. Data is compiled according to Standard Industrial Classification (SIC) codes 20–39 including chemicals, petroleum refining, primary metals, fabricated metals, paper, plastics, and transportation equipment.

Categories of on-site management include recycling, energy recovery, and treatment. TRI wastes are also injected underground or released to air, water, and land on site. Off-site management includes recycling, energy recovery, disposal, and treatment. Toxic chemicals that are geographically or physically separate from the facility reporting are classified as transfers.

TRI data for automobile manufacturing facilities are included in Transportation Equipment, SIC 37, which is designated for motor vehicles. Specific segments related to automobiles are Motor Vehicles and Car Bodies (SIC 3711), Truck and Bus Bodies (SIC 3713), and Motor Vehicle Parts and Accessories (SIC 3714).

TRI information for transportation relative to other sectors is shown in Figure 4.1.

Although transportation apparently makes only a small contribution to total TRI releases, many other sectors such as chemicals, primary metals, and plastics are major suppliers to the transportation sector. Table 4.1 provides a summary of TRI releases for SIC 371, which account for 64% of SIC 37 releases and transfers.

TABLE 4.1. 1993 TRI RELEASES FOR MOTOR VEHICLES SECTOR

Industry Sector	Releases Total (10^6 lbs)	Transfers Total (10^6 lbs)
Motor Vehicles (371)	98.7	168.0
Car Bodies (3711)	52.7	54.1
Truck and Bus Bodies (3713)	8.5	9.0
Vehicle Parts and Accessories (3714)	28.3	98.3

Source: U.S. EPA *Right to Know Network.*

The TRI releases and transfers per motor vehicle can be estimated using factory sales data from U.S. domestic plants of passenger cars, trucks, and buses and TRI data for SIC 371. Based on sales data from AAMA[2] and data in Table 4.1, 8.9 lbs of TRI chemicals are released per motor vehicle and 15.1 lbs are transferred.

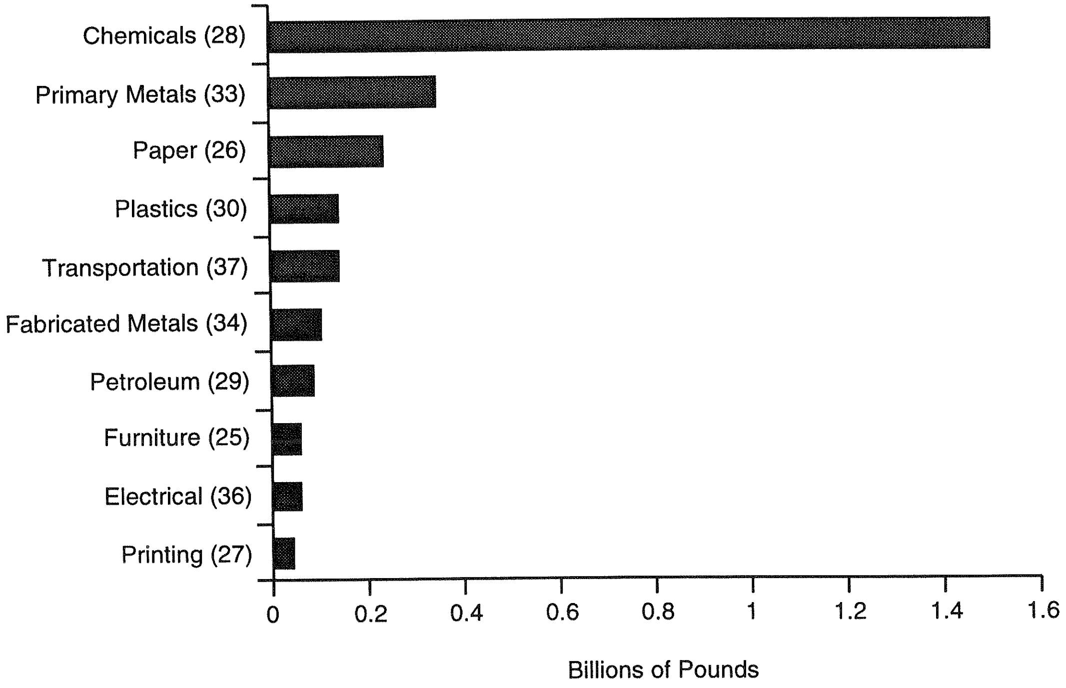

Fig. 4.1 TRI releases and transfers by sector. (Source: Ref. 1.)

Economic output per pound of pollutant emitted has been used to compare different TRI reporting industries. This approach again is limited because a large portion of the manufacturing activities that produce automobiles from natural resources and secondary materials occurs outside the manufacturing domain of the automotive industry.

The Automotive Pollution Prevention Project represents another source of data on the generation of toxic substances by the Big Three. This partnership between industry and government identified 65 persistent, toxic chemicals that significantly impact the Great Lakes. The Great Lakes persistent toxics (GLPT) are as follow[3]:

Halogenated Hydrocarbons	Dichlorobenzenes, ethylene dibromide, hexachlorobenzene, hexachlorobutadiene, hexachloroethane, methyl chloride, methylene chloride, nonachior, octachlorostyrene, pentachlorobenzene, polychlorinated biphenyls (PCBs), tetrachlorobenzene, tetrachlorodibenzodioxin (TCDD), tetrachlorodibenzofuran (TCDF), tetrachloroethylene, trichloroethylene, trichlorophenols
Nonhalogenated Hydrocarbons	Benzene, 2,4 dinitrotoluene, ethylbenzene, isophorone, nitrobenzene, phenol, phthalates (butylbenzyl phthalate, diethyl hexyl phthalate [DEHP], diethyl phthalate, dimethyl phthalate, di-n-butyl phthalate), polynuclear aromatic hydrocarbons [PAHs] (acenaphthalene, acenaphthene, anthracene, benzo (a) anthracene, benzo (a) pyrene, benzo (k) fluoranthene, chrysene, fluorene, indeno (1,2,3) pyrene, naphthalene, phenanthrene, pyrene), terphenyl, toluene
Metals	Antinomy, arsenic, beryllium, cadmium, chromium, copper, lead, mercury, nickel, selenium, silver, zinc
Pesticides	Aldrin, chlordane, DDD, DDE, DDT, dieldrin, heptachlor, lindane, mirex, oxychlordane, toxaphene

The Canadian Motor Vehicle Manufacturing Association has a similar program addressing pollution prevention involving the Big Three, the Federal Department of Environment, and the Ontario Ministry of Environment and Energy.[4]

Aggregate releases of GLPTs for Chrysler, Ford, and GM are provided in Table 4.2. These data are normalized for vehicle production. Until 1994, normalized releases were declining. Only two automobile company foundries that recycle galvanized metal account for nearly half of 1994 releases. The 1995 progress report for the Great Lakes Automotive Pollution Prevention Project[3] indicated that higher emissions may be due to increased reliance on and recycling of galvanized steel for body panel corrosion protection. An action team consisting of company and facility resources is examining reasons for the dramatic increase in zinc emissions relative to releases during previous years.

GM's 1994 Environmental Report provided a comprehensive characterization of its manufacturing activities. Table 4.3 summarizes total releases and transfers excluding recycling and energy recovery from GM manufacturing facilities.

Normalization on a unit production basis is complicated because these data include Delco Electronics (a division of GM Hughes) and GM's Power Products Group (Allison Gas Turbine, Electro-Motive, and Allison Transmission divisions), in addition to U.S. Automotive Operations. GM TRI releases and transfers in 1992 were dominated by point source and fugitive air emissions, which accounted for

TABLE 4.2. AGGREGATE RELEASES OF GLPTs BY AUTOMOBILE COMPANIES

	1988	1989	1990	1991	1992	1993	1994
TRI Releases of GLPTs (million lbs)	27.02	34.24	24.66	19.45	15.53	14.76	23.01
U.S. Vehicle Production (millions)	10.12	9.45	8.14	7.13	7.86	8.85	9.88
Pounds of GLPTs Released per Vehicle Produced	2.67	3.62	3.03	2.73	1.98	1.67	2.33

Increased releases in 1989 are partly attributable to a change in EPA threshold reporting requirements; two foundries account for nearly half of 1994 releases.
Source: Ref. 3.

TABLE 4.3. GM'S 1992 RELEASES AND TRANSFERS OF SARA TITLE III CHEMICALS

	Releases and Transfers (1000 lbs) Excluding Recycling and Energy Recovery					
Chemical	**Air**	**Water**	**Land**	**Public Sewage**	**Treatment/ Disposal**	**Total**
Xylene (mixed isomers)	8,861	0	0	14	440	9,270
Zinc (fume or dust)	91	1	4,299	1	0	4,392
Glycol Ethers	3,110	4	0	1,064	248	4,426
Acetone	3,016	63	0	16	78	3,173
Methyl Isobutyl Ketone	2,919	0	0	2	13	2,934
n-Butyl Alcohol	1,985	0	0	4	98	2,087
Hydrochloric Acid	1,111	0	0	972	2	2,085
Manganese Compounds	7	6	1,544	8	152	1,717
Zinc Compounds	22	4	1,003	27	591	1,647
Toluene	1,507	0	0	4	90	1,601
Ethylbenzene	822	0	0	1	732	1,555
Sulfuric Acid	57	0	0	305	1,130	1,492
Manganese	27	1	1,212	3	195	1,438
Methanol	1,248	0	0	29	69	1,346
Freon 113	1,148	0	0	0	12	1,160
1,1,1-Trichloroethane	802	0	0	0	7	809
Methyl Ethyl Ketone	772	0	0	3	23	798
Dichlorodifluoromethane (CFC 12)	516	0	0	0	0	516
Barium Compounds	6	0	0	3	368	377
Methylene bis (phenylisocyanate)	2	0	41	1	329	373
Others (53 chemicals)	1,480	39	689	609	625	3,442
Total	29,464	118	8,788	3,066	5,202	46,638

Source: Ref. 5.

63.2% of all releases and transfers. The other releases and transfers were distributed among water (0.25%), land (18.8%), public sewage (6.6%), and treatment/disposal (11.1%).

Further analysis of the data by GM environmental staff identified the sources responsible for the major environmental burdens. Approximately 56% of all releases and transfers originated from painting and coating operations. The main paint-related solvents—xylene, acetone, glycol ethers, methyl isobutyl ketone, n-butyl alcohol, and toluene—accounted for 75% of all reported air emissions by weight.

GM reported progress in reducing TRI chemical releases and transfers in its 1994 annual report. All TRI chemicals were reduced by 46% between 1988 and 1992. Targeted 33/50 chemicals were reduced by 50%, and chlorinated 33/50 chemicals were reduced by 79% during the same period.

Ford Motor Company reported TRI and 33/50 program data between 1988 and 1993 in its 1995 Environmental Report. Figure 4.2 shows TRI releases and transfers but excludes recycling and energy recovery. Ford estimates that 6% of releases were to water, 5% to land, and the remaining 89% to air. Figure 4.3 normalizes releases and transfers data by production.

Hazardous waste generation by automotive manufacture is relatively small in comparison to the amount of nonhazardous waste produced. In 1994, GM recorded 74,500 tons of hazardous waste as defined under RCRA and TSCA, compared to 3.5 million tons of nonhazardous waste. Thus, hazardous waste represents only 2.1% of GM's total solid waste. A large fraction of nonhazardous waste is recycled or combusted with energy recovery. In 1994, approximately 47% of nonhazardous solid waste was composed of metal scrap, of which 98.4% is recycled. Of all nonhazardous

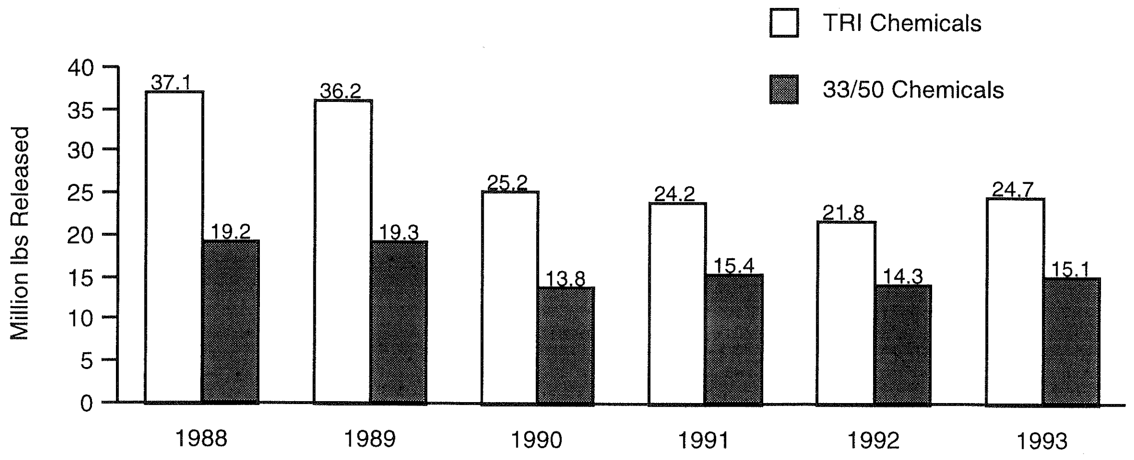

Fig. 4.2 Ford TRI and 33/50 releases and transfers. (Source: Ref. 6.)

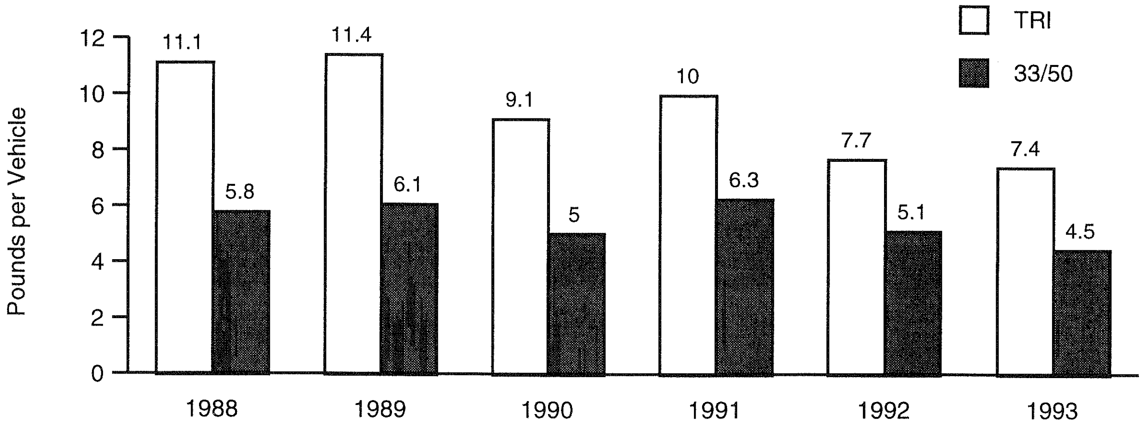

Fig. 4.3 Ford TRI and 33/50 data per vehicle produced. (Source: Refs. 2 and 6.)

waste, 58.7% is recycled and 2.4% is managed through combustion with energy recovery.[7]

An estimate of the relative contribution of TRI releases and transfers (excluding recycling and energy recovery) to the total waste generated by automotive manufacturing is shown in Figure 4.4.

Further analysis of 1994 plant waste by GM indicated that packaging waste accounted for 350,000 tons, 41% of which was recycled, 43% landfilled, and 11% combusted with energy recovery.[7] Packaging recycling and source reduction techniques have been successfully applied to several GM assembly plants. Waste reduction progress made at eight GM assembly plants that set a goal of zero waste to the landfill is indicated in Figure 4.5. This pilot project demonstrates the tremendous potential of source reduction in reducing plant waste. The average assembly plant packaging waste is estimated at 25 lbs/vehicle.

4.1.2 Energy

It is difficult to obtain disaggregated data for part fabrication and assembly energy requirements. Sullivan and Hu[8] estimated an average energy intensity of 7500 BTU/lb to manufacture a typical Ford vehicle. This value was based on the total energy consumed by Ford facilities, which was equivalent to 16 MBTU per vehicle. Adjustments were made to obtain the primary energy consumption for part fabrication and assembly using appropriate energy conversion efficiencies.

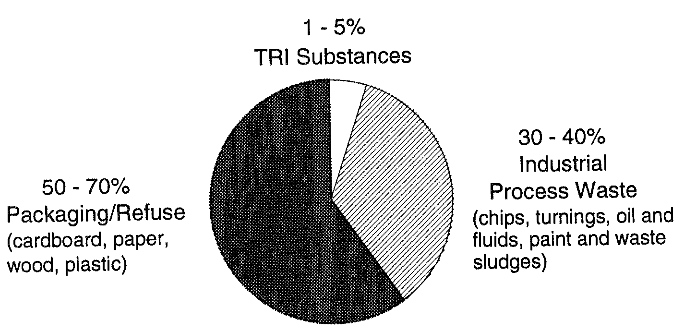

Fig. 4.4 Estimated proportions of waste production in automobile manufacturing. (Courtesy of Phil Lawrence, Environmental Quality Office, Ford Motor Company.)

TABLE 4.4. GM ENERGY USE AND PRODUCTION

	Energy Use (TBtu)	GM U.S. Vehicle Production (1000)	Energy Use per Unit (MBtu)
1990	132.6	4,123.5	32.1
1991	130.7	3,580.3	36.5
1992	126.4	3,848.7	32.8

Includes GM U.S. Automotive Operations, Delco Electronics (a division of GM Hughes), and GM's Power Products Group (Allison Gas Turbines, Electro-Motive, and Allison Transmission divisions).
Source: Ref. 5.

Energy use by U.S. GM manufacturing facilities is shown in Table 4.4. This data does not represent the full energy cycle (total primary energy) for electricity or fuels such as coal or fuel oil. Energy use data reported by GM includes energy to produce coke. Thus, steel production energy is included in the data from Table 4.4 which indicates that some material production energy is combined with GM part fabrication and assembly data. Another major difficulty in evaluating the total parts fabrication and assembly energy lies in accounting for energy consumed by suppliers that fabricate parts.

4.2 Public Policy and Legislation

Automobile manufacturing activities are affected by myriad environmental regulations at the federal, state, and local levels. Federal regulations addressing automobile manufacturing most broadly are the Clean Air Act (CAA), the Clean Water Act (CWA), the Resource Conservation and Recovery Act (RCRA), Superfund Amendments and Reauthorization Act (SARA) of 1986, and the Pollution Prevention Act of 1990. Recent amendments to the CAA, SARA, CWA, and other proposed rule-makings have changed the environment for automobile manufacturing in the late 1980s and early 1990s. Intense competition from Japanese and other overseas manufacturers has also prompted dramatic changes in automobile design and manufacturing processes. Total Quality Management (TQM), just-in-time inventory control, and lean production techniques are a few of the initiatives being implemented by domestic manufacturers and suppliers to maintain global competitiveness. These initiatives, particularly lean manufacturing techniques that minimize inputs during production, often make production cleaner as well.

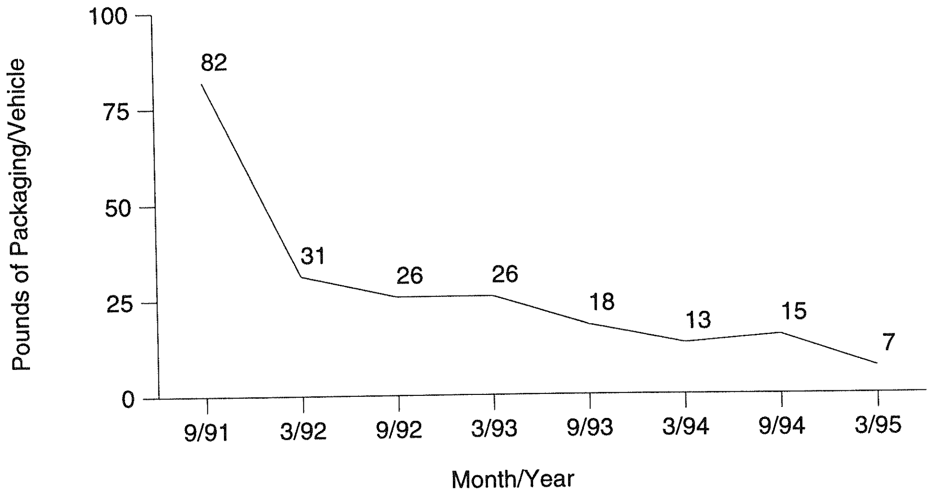

Fig. 4.5 Packaging reduction at eight GM assembly plants. (Source: Ref. 7.)

Thus, whether legislation or overseas competition has been the main driver of improvements in environmental performance and competitiveness in the North American automotive industry is difficult to ascertain. Industry expenditures on pollution control technology are one way to gauge the amount of resources that manufacturers have devoted to reducing pollution.

Table 4.5 shows automotive industry financial outlays for pollution abatement generally increasing from 1988 to 1992. Operating expenditures for solid waste abatement are significant and are partly a function of landfill disposal costs. Air pollution abatement commands a significant portion of capital outlays. The Common Sense Initiative, Auto Sector, has identified certain provisions of the Clean Air Act Amendments (CAAA) of 1990 as especially burdensome and costly among the federal regulatory framework affecting automobile manufacturing; in particular, they cite the following provisions of the CAAA of 1990–Section 112, Title V, and New Source Review (NSR).

The CAAA of 1990 established national, technology-based emissions standards for 189 listed hazardous air pollutants (HAPs). The HAP list is based on the potential health and environmental hazards of air toxics.[9]

Stationary sources that emit more than 10 tons per year of a listed HAP or 25 tons per year of any combination of HAPs are subject to §112 of the CAAA. CAAA §112 promulgates standards for each source category that require installation of maximum available control technology (MACT). MACT standards are intended to provide for emission reductions of 95%.[10] Corporations may be fined up to one million dollars if found criminally knowledgeable about HAP releases that place persons in imminent danger, and up to $200,000 if found criminally negligent.[11]

The NSR provisions of the CAAA subject new sources of air pollution and existing sources undergoing significant changes to review and permitting. New and significantly modified sources are subject to more stringent air pollution standards than existing sources. These standards are determined in part by whether the new or modified source of air pollution is located in a CAAA nonattainment area under the National Ambient Air Quality Standards (NAAQS) for six criteria pollutants: sulfur dioxide, nitrogen dioxide, particulate matter larger than 10 microns in diameter, carbon monoxide, ozone, and lead (40 CFR 50, 1993). CAAA attainment areas are subject to the Prevention of Significant Deterioration (PSD) program, which requires a permit for new or modified sources that have the potential to emit more than a certain tonnage per year of a regulated pollutant.

The EPA has proposed changes to the NSR requirements to comply with more stringent standards for preconstruction review of new and modified sources. These changes may make it more costly for OEMs or their suppliers to receive approval for construction of new or modified facilities located in nonattainment areas.[12]

Title V of the CAAA requires states to administer a permit program for the operation of sources of air pollutants. States

TABLE 4.5. AUTOMOTIVE INDUSTRY EXPENDITURES ON POLLUTION ABATEMENT AND CONTROL ($ MILLIONS)

	1988	1989	1990	1992
Capital Expenditures[a]				
Air	$ 59.7	$ 122.1	$ 185.7	$ 141.1
Water	35.2	55.3	88.0	23.8
Solid Waste	26.5	24.2	26.4	8.6
Subtotal	$121.5	$201.7	$300.1	$173.8
Operating Expenditures[b]				
Air	164.2	167.0	183.7	218.7
Water	167.4	162.0	173.9	215.8
Solid Waste	165.8	219.2	260.4	226.2
Subtotal	$497.4	$548.2	$618.0	$660.6
Total	$618.9	$749.9	$918.1	$834.9

[a] Does not include expenditures for noise abatement and automobile emission abatement devices; these figures are not adjusted for production volumes.
[b] Does note include payments to government for public sewage services and solid waste collection and pickup.
Source: U.S. Department of Commerce, Bureau of the Census.

are to collect fees from sources to cover the administrative costs of the program. By requiring each source to prepare a compliance plan, the permitting process effectively establishes how much of an air pollutant a source can emit. Sources must apply for a permit renewal after five years.

Other federal regulations, including RCRA, the Pollution Prevention Act of 1970, and Superfund legislation, also affect automotive manufacturing activities, although to a lesser extent than the CAAA of 1990. The 1984 amendment to RCRA, known as the Hazardous and Solid Waste Act, requires hazardous waste generators to create programs to reduce the volume and toxicity of their wastes wherever economically feasible. This amendment has encouraged OEMs to reduce the use of trichloroethylene and cadmium, and has influenced industry packaging reduction initiatives.

Traditionally, pollution policy in the United States has focused on releases to specific environmental media—land, air, and water. This approach often encourages transfer of a pollutant to another medium rather than elimination of the pollutant. The Pollution Prevention Act of 1990 (PPA) codified pollution prevention and source reduction as national policy. The EPA has developed a pollution prevention hierarchy as part of its strategy to promote effective pollution prevention activities. This hierarchy has been adopted as a guiding principle by the automotive industry in its source reduction programs. The pollution prevention hierarchy is as follows[13]:

- Source reduction and prevention whenever feasible first, then
- Responsible recycling, then
- Treatment, then
- Disposal or other release into the environment as a last resort

Section 6607 is the only explicit mandate contained in the PPA which affects OEMs. It expands SARA 313 TRI data requirements to include information on the amounts of *all* toxic SARA chemicals entering the waste stream before treatment, energy recovery, recycling, or disposal, as well as techniques and source reduction practices used at facilities (PPA 6007, 42 USCA 13106).

The automotive industry, as one of the oldest and largest industries in the United States, has many inactive sites that fall under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), or Superfund regulations. GM's Corporate Environmental Report states that the company has been identified as a potentially responsible party for 200 sites.[5] GM's Superfund expenditures from 1981 to 1992 were $84.9 M. GM and the other OEMs have established reserve funds for potential future Superfund liabilities.

4.3 Design Initiatives and Management Opportunities

4.3.1 OEM Environmental Management Programs

The most significant development in pollution prevention by manufacturers during the past five years is the willingness of the Big Three CEOs and top management to endorse environmental management systems (EMSs) and to incorporate pollution prevention and other proactive environmental measures into business plans. Without support coordinated at this level of decision-making, midlevel managers and plant employees may lack incentives to reduce the environmental impact of manufacturing activities.

Results of specific OEM pollution prevention manufacturing initiatives, such as packaging and toxics reduction, are encouraging, but progress on other environmental issues such as supplier performance is uncertain. Because cost and operational flexibility will continue to be of paramount competitive importance to OEMs and their suppliers, pollution prevention projects that address these variables will be more successful.

Other mechanisms for improving environmental performance in manufacturing are emerging. ISO 14000 is a set of international environmental standards for business in development at the Swiss-based International Standards Organization's Technical Committee 207 (TC 207). The goal of TC 207 is to make ISO 14000 the prevailing environmental standard and to then merge it with ISO 9000, an established quality management standard that has been well received by the international manufacturing community. The effectiveness of ISO 14000 in reducing environmental impacts is difficult to predict. Ensuring that companies have an EMS in place is important, but these standards do not provide specific guidance on how to establish goals and policy and translate them into actions on the operational level. ISO 14000 emphasizes manufacturing activities rather than product stewardship.

Another significant change in the way domestic OEMs conduct their manufacturing activities is a trend toward reducing the number of suppliers providing a particular component or service. Additionally, OEMs are integrating their remaining suppliers more fully into operations by having suppliers provide services at the plant level. GM's Chemicals Management program exemplifies this shift toward integration and illustrates how including suppliers in decision-making at the plant level and changing their profit incentives can augment pollution prevention. Suppliers also may improve their own environmental performance by observing OEM practices. However, no formal mechanisms currently exist for transferring pollution prevention technology or methods to suppliers.

Despite substantial progress during the last ten years, OEMs face obstacles to further improving pollution prevention. The industry is extremely competitive with narrow profit margins. In spite of common concerns regarding many portions of the regulatory framework for manufacturing, competitiveness issues will continue to limit cooperation and technology transfer among OEMs. Difficulties in measuring the financial benefits of investments in waste reduction and pollution prevention should be mitigated somewhat by improved risk assessment techniques and the emergence of activity-based costing (ABC). ABC assigns pollution prevention and regulatory expenditures such as permitting, which are usually lumped into facility overhead costs, to particular product lines. But even with improvements in financial assessment, OEMs will face increasing marginal costs when attempting further reductions in categories that demand intensive capital or labor expenditures (such as large additional TRI reductions).

Each domestic OEM has an environmental staff responsible for managing environmental issues. Environmental management systems, which include the policies, processes, procedures, and the organization supporting environmental management, were described in Chapter 2. Although the issues facing OEMs are similar, their systems for managing environmental issues differ somewhat in structure and function. In general, their EMSs are functionally organized between the management of the manufacturing facility and processes and the management of vehicle use and retirement, which includes vehicle emissions, fuel economy, and recycling. Each OEM has a corporate vice president who administers the environmental programs. Pollution prevention plans coordinated by the OEM's EMSs have focused principally on reducing usage of materials of concern, packaging and shipping wastes, chlorofluorocarbons, energy, and emissions of hazardous wastes and VOCs from painting during manufacturing and assembly.

Chrysler

Environmental management and policy at Chrysler is conducted by its Environmental and Energy Affairs staff. Today, part of Chrysler's corporate philosophy is to embrace constant change and to engage in voluntary actions to achieve early reductions of environmentally sensitive materials, thereby minimizing the impact of reactive regulatory mandates. The following are examples of recent pollution prevention efforts at Chrysler[14]:

Action	**Outcome**
Elimination and Reduction of Materials of Concern	Elimination of hexavalent chromium from all materials and processes
Recycling Used Oil	8 M gallons of used oil from stamping, machining, and engine plants recycled annually
Solid Waste Recycling	Eliminated 55% of expendable packaging wastes from assembly plants
Paper Recycling	800 tons of paper recycled per year
Painting	Reduced per vehicle volume of paints and solvents by 50% over 10 years First to convert to high solids basecoat/clearcoat technology (BC/CC) (Other painting initiatives include block painting a set of vehicles the same color to increase solids contained in coatings and to reduce absolute volume of coating per vehicle, thereby reducing VOCs)
Hazardous Wastes	Elimination of chlorinated solvents used in electronics manufacture, parts cleaning, and degreasing; substitution of hazardous materials with nonhazardous materials; recycling of lead acid batteries

Chrysler won the President's Environment and Conservation Award and an EPA Administrator's Award for its Jefferson North Assembly Plant. This plant, built on a

283-acre reclaimed site in Detroit, incorporates certain pollution prevention technologies on a large scale, including secondary containment mechanisms for underground piping, wet sumps and trenches, aboveground wastewater pipelines and storage tanks for visual leak inspection, and an on-site wastewater treatment facility.

Ford

Ford Motor Company's formal written environmental policy is contained in *Policy Letter 17: Protecting Health and the Environment*, which provides various directives for guiding company operations. One such directive led to Ford's *Guide to Manufacturing Environmental Leadership*. This guide focuses on three areas:

Materials	Ford's stated goals are to reduce or eliminate the use of materials of concern (e.g., PCBs, halogenated solvents, and heavy metals) and to reduce, reuse, and recycle packaging materials and other industrial materials (e.g., sludges, oils, drums, and solvents)
Processes	Product programs should consider environmental objectives in design; environmental impact analyses will be made for each step of the manufacturing process; energy efficiency improvement programs will improve monitoring and reduce the use of energy
Facilities	Wastes and contaminated soils at Ford sites will be removed or contained; facilities will develop and maintain emergency plans; business plans will include programs for protecting and enhancing wildlife habitats at or near Ford facilities

Ford also publishes an Environmental Report that highlights environmental initiatives and offers data on environmental performance.[6] The following list provides several examples of Ford's environmental initiatives:

Use of "No Clean" Solder	A combination of "no-clean" solder and inert gas wave technologies has been used as a substitute for CFC solvents for cleaning electronic circuit boards
Granulated Walnut Shells as a Cleaning Agent	In a Köln, Germany plant granulated walnut shells are being used to clean seat molds as a substitute for chlorinated hydrocarbon solvents
Reduced Paint Emissions	Ford's Galaxy Multipurpose Vehicle assembly plant has achieved the lowest emissions among similar facilities in Europe through use of water-based primer paints, a clearcoat facility that can use either water- or solvent-based paint, and special incinerators
Recycling Foundry Sand	Foundry sand from the Ford casting plants in Windsor, Ontario and Cleveland, Ohio is being recycled for use as paving and building material; approximately 115,000 metric tons of sand are diverted from landfills annually
Reusable Containers	European and North American suppliers are being requested to ship parts in reusable and returnable containers; at the Romeo, Michigan Engine Plant, more than 90% of all parts now are shipped in returnable containers
Recycling Waste	North American assembly plants are recycling 380 million pounds of waste each year

GM

In 1991, GM adopted a set of Environmental Principles to internally communicate the corporation's environmental commitments to employees so they can be effectively integrated into business practices. In 1992, GM restructured its environmental staff that evolved to a Worldwide Facilities Group and Corporate Affairs, who are jointly responsible for developing and coordinating policy on energy, emissions control, pollution prevention, remediation, and other environmental issues. Individual divisional staffs and facilities have responsibility for implementing environmental policy. In 1994, environmental performance began to be evaluated at the operating unit level and incorporated into compensation reviews.

GM's Environmental Principles explicitly recognize the product life cycle system. The second principle states: "We are committed to reducing waste and pollutants, conserving resources, and recycling materials at every stage of the product life cycle." GM also has committed to the CERES principles. CERES, the Coalition for Environmentally Responsible Economies, is a national organization of environmental and investment groups addressing social responsibility. These principles include informing the public about environmental performance. GM's annual environmental report represents one of the most informative and comprehensive reports relative to other major corporations.

Environmental initiatives at GM related to manufacturing facilities include the WE CARE program and the Chemicals Management program. WE CARE, an acronym for Waste Elimination and Cost Awareness Reward Everyone, was initiated in 1990 and further expanded in 1992 throughout GM facilities in North America and Mexico. WE CARE emphasizes source reduction of wastes and reduced use of raw materials (especially toxics). Many WE CARE strategies are generated by GM's employee suggestion plan. GM estimates that facility pollution prevention projects have reduced or prevented 318,000 tons of emissions and wastes.[5]

GM has estimated the following relative potentials for different categories of waste reduction:

- Product-related materials 38%
- Process-related materials and chemicals 38%
- Packaging waste management 14%
- Waste management methods 10%

GM packaging waste initiatives are saving an estimated 150,000 cubic yards of landfill space annually through the use of packaging guidelines applicable to all GM facilities and suppliers. Guidelines suggest using corrugated pallets for loads less than 500 lbs, breakaway pallet cartons, and uncolored, coded PE stretch wrap. In addition, EPS foam, lead, and cadmium are targeted for elimination. Plastics used in packaging are identified, and only similar materials are bonded together. Using these guidelines, eight GM assembly plants have set goals of sending zero packaging waste to landfills. Figure 4.5 shows the progress made to date.

Packaging reduction initiatives such as those of GM illustrate how a manufacturer can positively influence its suppliers' environmental performance. This may then benefit other OEMs that source from common suppliers.

GM's Chemicals Management program has substantially reduced chemical volumes and expenditures while changing the OEM-supplier relationship in a unique way. GM designated a single, first-tier supplier to provide chemicals and chemical services to a GM facility. This primary supplier is then responsible for acquiring chemicals from secondary suppliers and for providing chemical management, analysis, and inventory control to GM, effectively becoming part of GM's production team. GM pays the primary supplier a flat annual fee, thereby removing the supplier's incentive to sell large volumes of chemicals. Those plants implementing the program (more than half of the North American plants) have reduced chemical use by an average of 30%.[5]

GM also participates in voluntary programs such as EPA's 33/50 and WASTEWISE programs, the Conference of Northeastern Governors Packaging Challenge, the National Office Recycling Project, and the Great Lakes Automotive Pollution Prevention Project.

4.3.2 Partnerships Between Industry and Government

Great Lakes Automotive Pollution Prevention Project

Initiated in the fall of 1991, the Great Lakes Automotive Pollution Prevention Project is a first-of-its-kind public/private partnership between the Big Three OEMs and the State of Michigan (on behalf of the Great Lakes States and EPA) addressing environmental impacts of automotive manufacturing. The partnership is administered by the AAMA and the Michigan Department of Natural Resources. The project focuses on reducing generation and release of toxics in the Great Lakes Basin through the following initiatives[15]:

- Identifying Great Lakes persistent toxics (GLPT) and reducing releases beyond regulatory requirements—GLPT are defined as known to be present in the Great Lakes ecosystem, bio-accumulative in animals and plants, and reported to demonstrate toxicity to animal or plant life
- Advancing pollution prevention efforts at the OEM level and among the supplier base
- Addressing regulatory barriers that inhibit pollution prevention.

A 1994 Progress Report showed that releases of GLPT substances from automobile companies declined by 20.2% in the first year, or 28.9% when adjusted for lower production volumes.[15] The OEMs also submitted sixteen case studies documenting pollution prevention initiatives within their manufacturing operations. These case studies describe successful OEM pollution prevention initiatives with the intention of facilitating technology transfer among OEMs, suppliers, and other industries. Examples include the following[15]:

Chrysler	Material screening example: a supplier-provided transmission fluid containing butyl benzyl phthalate (a persistent toxic identified for reduction) was refused and a suitable substitute found
	Mercury use in testing was reduced by modifying specifications, decommissioning equipment, and evaluating alternative equipment
	Eliminated chromium from radiator paint to avoid having overspray sludge designated as hazardous waste; substituted a water-based product which also substantially reduced VOC emissions
	Surface coatings toxic reduction program aims to eliminate or reduce by 75% VOCs/toxics through process changes or material substitutions by 1996, while simultaneously targeting elimination of lead and hexavalent chromium from coatings
	Targeting elimination of PCBs by 1998 from all uses in transformers, capacitors, oils, etc.
Ford	Through process changes, reduced annual toluene releases by 23,000 lbs from one plant and reduced annual trichloroethylene releases by 50,000 lbs at another site; replaced a trichloroethylene-based degreasing system used for all heat exchangers with an aqueous process
	Taking steps to institutionalize waste prevention into routine manufacturing operations by producing a guidebook and implementing projects at plants to identify opportunities for reduction
General Motors	Found a water-based adhesive for attaching soft trim; this reduced VOC emissions by 20 tons per year and converted hazardous, solid process wastes to nonhazardous
	New paint booth cleaning methods at one plant resulted in a 40% reduction in VOC emissions from purge solvents per vehicle
	Removed CFC-containing materials from the list of approved purchases; one plant using 15,000 lbs of aerosol can CFC degreasers annually substituted an HCFC product while simultaneously reducing use by up to 40%
	Eliminated the use of lead or other hazardous heavy metals as a stabilizer in PVC wiring harnesses; this eliminated hazardous wastes from processing operations
	Substituted a solvent-free adhesive at one plant, reducing toluene emissions by 300 tons per year

A 1993 critique of the accomplishments of the Automotive Pollution Prevention Project by the Ecology Center of Ann Arbor stated that automobile companies have not proactively sought compliance with their programs from suppliers, which are a critical source of pollutants.[16] The critique also concludes that the OEMs have initiated few significant new pollution prevention projects and that most reductions have resulted from of pre-existing programs. Finally, the report also contends that the automobile companies have not provided plant-by-plant or process-by-process surveys of pollution generation as promised.

The Automotive Pollution Prevention Project's second progress report, which was recently published, includes data presented previously in this chapter. In addition to TRI data from 1994, this report presents TRI data on off-site transfers and lists their sources. Each automobile company's environmental policy and general pollution prevention process, including the development of an external advisory committee, are outlined. Further case studies are then presented.

Chrysler, Ford, and GM have made progress in a few common areas—packaging waste reductions, elimination or reduction of some materials of concern, and reduction of paint shop emissions. To date, these common improvements are more a function of a common regulatory framework and economic incentives rather than a high degree of technology transfer among OEMs. The extreme competitive pressures of automobile manufacturing will limit technology transfer among OEMs to a degree, but programs such as the Automotive Pollution Prevention Project and the Common Sense Initiative offer a good forum for interaction among environmental staff. Environmental staff must continue to pursue influence on design, manufacturing, and facilities management.

Common Sense Initiative

In 1993, the EPA, under Administrator Carol Browner, adopted a new approach to environmental protection called the Common Sense Initiative (CSI). The CSI recognizes that the current federal regulatory framework often imposes significant costs for environmental improvements in addition to promulgating inconsistent and inflexible standards. The CSI is focused on finding opportunities to improve environmental performance in a cost-effective manner in automobile manufacturing and five other pilot industries. The broad aims of the CSI are to develop innovative, consensus solutions that measurably improve public health and the environment by allowing industry to use creative technologies and flexible approaches; that is, "cleaner, cheaper, smarter" solutions. Industrywide pollution prevention will be emphasized over end-of-pipe controls and the current focus on individual pollutants. Multistakeholder participation is an important goal of the CSI; its intention is to improve the sometimes adversarial relations among industry, government, community, environmental, and labor groups.

Examples of obstacles to improvement identified in early CSI Auto Sector group discussions include the following:

- The automotive industry is dynamic, constantly responding to the changing needs of the marketplace. The current command and control system makes it difficult for the automotive industry to respond to the regulatory framework in a cost-effective way. For instance, the permitting process is slow and often can constrain even small changes in manufacturing operations and processes because of onerous terms/conditions and/or unreasonable timelines.
- Lack of trust among stakeholders, especially at the community level, continues to exist. OEMs often choose to focus their resources on meeting top-down federal regulations rather than interacting with community stakeholders.
- Various disincentives exist which limit OEM attempts to implement innovative pollution prevention methods and technologies. These innovations are risky for industry to implement because they may not immediately produce better results than existing best-available technologies, such as rigid hazardous waste listings under RCRA and the NSR process under the 1990 CAAA.
- Reporting requirements often are too complex. Reporting is sometimes redundant, poorly or inconsistently formatted, and of questionable usefulness to the public or government. Examples include the use of MSDS and OSHA requirements to gather data on chemicals.
- Disincentives to industry self-auditing and self-compliance exist.

The CSI Auto Sector participants have broken into Work Groups addressing Life Cycle Management/Innovative Technology, Permitting, Community Technical Assistance and Involvement, and Regulatory issues. An Alternative Sector Regulatory System project will attempt to create a paradigm shift by developing a set of approaches designed for actual circumstances at automobile manufacturing plants. Each Work Group intends to have a set of tangible recommendations for improvements to the current regulatory framework within a year of the CSI's inception.

The CSI is one of five new EPA programs aimed at enhancing environmental protection while reducing administrative costs and burdens associated with current regulations. The other four new activities are as follow:

- Project XL (Excellent Leadership), designed to promote greater regulatory flexibility
- Environmental Leadership Program
- Multimedia Permitting
- Design for the Environment

These new programs, coupled with improvements in the current federal regulatory system, are intended to provide industry with the flexibility to test alternative environmental improvement strategies while also allowing environmental regulators the opportunity to propose cleaner, cheaper, and smarter approaches.

Low Emission Paint Consortium (LEPC)

This industry consortium was founded in 1993 as part of the U.S. Council for Automotive Research (USCAR). Its mission is to conduct research on emerging paint-related technologies to reduce solvent emissions from paint systems. The most promising technologies developed to date are powder clearcoat applications which produce no hydrocarbon emissions. Engineers from the Big Three have constructed and are currently operating a new facility to pilot test the application of powder clearcoat technologies.

Pollution Prevention Opportunities in Painting and Coating

Automotive coating (painting) accounts for a large fraction of the VOC emissions from automotive manufacturing. The specific magnitude of the burdens were quantified previously in this chapter. Because of their relative importance, opportunities to reduce paint-related burdens will be briefly addressed here.

VOC emissions occur during application, curing, and equipment cleaning operations. Additional environmental impacts from painting result from wastes generated from overspray, removing defective coatings, and color changeovers.

Fifty solvents that are found in paints and adhesives are among the 189 HAPS regulated under the Clean Air Act.[17] In addition to the CAA and other federal regulations under the CWA and RCRA, many assembly facilities also must comply with local and regional regulations that restrict VOC emissions.

Several paint technologies are emerging which seek to reduce the VOC burden associated with conventional solvent-based paints. Current alternative technologies are high solids, solvent-borne coatings; powder coatings; waterborne coatings; and ultraviolet- or electron beam-cured coatings. Technologies under development include vapor injection cure coatings, supercritical carbon dioxide as a solvent, and radiation-induced, thermally cured coatings. Each technology offers unique benefits which must be balanced against its limitations. Strategies for improving paint technologies are both product and process oriented.

Conventional paints consist of four basic components, including pigments which protect and strengthen the film and impart aesthetic appeal, binders or film formers which bind pigment to the painted surface, solvents which serve as a vehicle to apply the paint, and other additives such as corrosion inhibitors and biocides.

Some advantages and limitations of alternative paint technologies are shown in Table 4.6.

TABLE 4.6. ADVANTAGES AND DISADVANTAGES OF VARIOUS PAINT TECHNOLOGIES

Paint Technology	Advantages	Disadvantages
High Solids Coatings, Solvent-Borne	Contain a lower concentration of solvents than odor, conventional coatings, reducing environmental, safety, and health problems Require less energy to manufacture and cure Compatible with application equipment for conventional coatings	Require lower viscosity resins which may cause excessive flow; additives are available to control flow and sagging, but may reduce gloss Thicker films may blister during baking Overspray tends to create a sticky mass, which can create problems with clogging, collection and disposal Viscosity of high solids paints is highly sensitive to temperature A longer curing time is required
Powder Coatings	No solvents used in the coating formulation High transfer efficiency Thick coatings can be applied in one pass, even over sharp edges	Need to treat the substrate with high temperature (500 degrees Fahrenheit) to melt powder Restricted to metallic substrates only and small parts that can be placed in a baking oven Color changes and color matching are more difficult
Waterborne Coatings	Substitute water for a portion of the solvent used as the resin carrier in typical organic coating formulations (substantial quantities of organic solvents also may be present) Some water reducible coatings allow overspray to be recovered and recycled Good to excellent surface properties Simpler cleanup Existing equipment can be used for application, but stainless steel inserts are required	More expensive High gloss more difficult to achieve Longer drying time More energy can be required to force-dry or bake waterborne coatings than comparable solvent formulations because of the high latent heat of evaporation for water (energy requirements may be four times greater for water-based coatings) Humidity control in the application and curing areas is required
Electrodeposition	Uses waterborne coatings with reduced levels of VOCs Closed-loop operations eliminating VOC emissions is possible High transfer efficiency	High capital expense To produce a high gloss finish, the coating must contain a conductive pigment Limited to steel, aluminum, and other metals

Source: Ref. 18.

Other coating alternatives include automotive films that can be applied to metal and plastic substrates. VOCs are generated during film manufacture rather than at OEM facilities. The environmental burdens of this process are currently under investigation by NPPC. For plastic parts, paint film can be applied by injection or vacuum molding. Another technique for providing color to plastic parts is in-mold paint.

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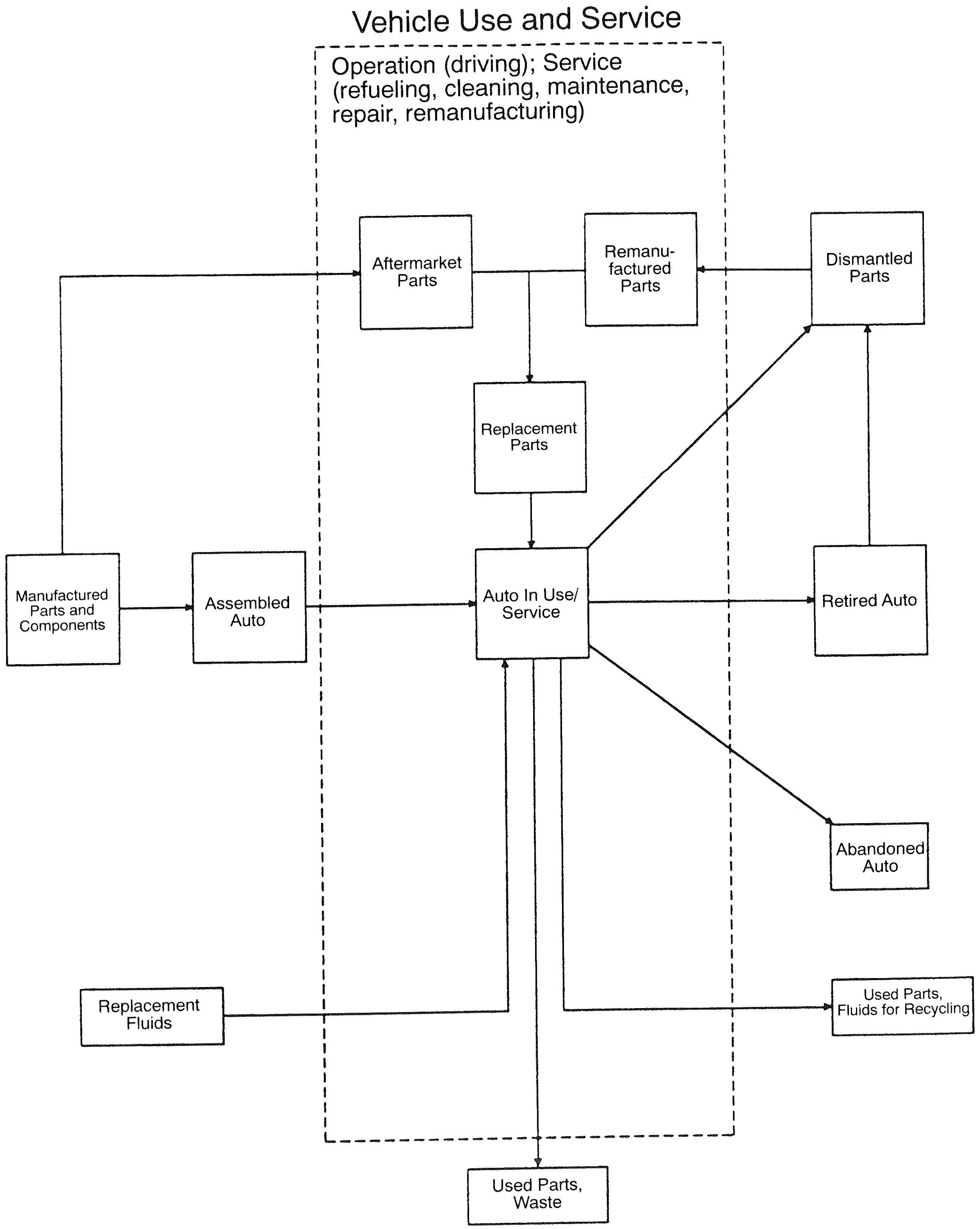


Chapter 5

Vehicle Use and Service

Automobile use and ownership in the United States has reached epic proportions. Americans drove their motor vehicles almost 2.3 trillion miles in 1993, as many miles as the rest of the world combined. Passenger cars and two-axle, four-tire trucks (light-duty trucks) accounted for 93% of the vehicle miles traveled (VMT).[1] The growth in U.S. VMT for highway vehicles has averaged 3.3% a year from 1970 to 1990 and is expected to continue at an annual rate of 2 to 2.5%, although U.S. population and GNP growth rates have slowed.[2,3] There are now 148 million automobiles in the United States, or 34% of the world total. With only 5% of global population, the United States consumes a quarter of the world's oil, and its reliance on imported oil is increasing.[4] In 1985, imported oil accounted for 27% of total U.S. oil consumption. In 1994, imported oil accounted for 45% of the total,[5] and the U.S. Department of Energy (DOE) projects that oil imports will reach 56% by the year 2015.[6]

When summed across 148 million units and 2.3 trillion VMT, automobile use represents one of the most energy-intensive and polluting human activities. The use stage dominates overall environmental impacts of the vehicle across its life cycle. Environmental burdens of automobile use are determined by numerous variables—technology, design, consumer demand, driver behavior, government policy, road and highway networks, land use patterns, and even weather patterns. Scientists, economists, environmentalists, and government officials are grappling with a similar problem: which variables will provide the best opportunities for reducing the environmental and social impacts of automobile use at the least cost?

5.1 Environmental Burden

Advocates for energy efficiency, public health, and the environment contend that the true social costs of the personal mobility allowed by automobiles are grossly underestimated because they are not fully reflected in the explicit costs of driving: purchase price, gas, insurance, taxes, and repairs. These other costs are known as externalities because they are external to market transactions. Externalities from automobile use include resource and energy depletion, air pollution, global warming, vehicle maintenance, pollution, impacts from infrastructure maintenance and new construction, congestion, noise, increased national security risk from relying on foreign oil, and degradation of natural habitats.

5.1.1 Resource Depletion

Resource inputs for automobile use include product, process, and distribution components. In addition to the automobile itself, product component inputs in this stage include replacement parts such as tires, hoses, wipers, lights, belts, clutch discs and plates, spark plugs, air filters, batteries, brake shoes and pads, oil filters, and fuses from normal wear. Other parts and components may be required to repair a vehicle damaged in an accident. Process components include gasoline, oil, fuel and oil additives, lubricants and greases, transmission and brake fluid, power steering fluid, washer fluid, coolant/antifreeze, refrigerants, and the packaging associated with these items. Highway infrastructure is a resource-intensive process component. The distribution component includes the packaging associated with replacement parts.

5.1.2 Energy

One of the most serious environmental issues facing the automobile is its enormous consumption of nonrenewable energy. Consumption of nonrenewable energy by the automobile challenges the ecological and economic sustainability of this product system. Energy statistics for the transportation sector and the automobile demonstrate the magnitude of the problem. In 1992, transportation accounted for 65.1% of total petroleum consumption in the United States; automobiles and light-duty trucks consumed 58% of the transportation total.[7] The transportation sector accounted for 27.3% (22.46 quads) of total U.S. energy use (82.14 quads) in 1992.[8] Automobiles consumed 9117.6 trillion Btu of gasoline and 122.9 trillion Btu of diesel fuel; light-duty trucks consumed 4001.6 trillion Btu of gasoline and 151.7 trillion Btu of diesel. The total energy consumed in using gasoline also includes the energy required in drilling petroleum and refining it into gasoline.

A summary of energy use for different modes of passenger travel is presented in Table 5.1. This table shows total vehicle miles traveled by each mode.

Analysis of the energy intensities of alternative passenger modes measured in Btu per passenger mile is also provided in Table 5.1. These data indicate that intercity and school buses, followed by motorcycles, represent the least energy-intensive modes. These energy intensities were calculated using actual fuel consumption and passenger miles traveled, or VMT and a passenger load factor. The load factor significantly affects the energy intensity. The average Btu per VMT is 5767 for automobiles and 8781 for trucks based on 1991 data.[7] Car-pooling with four passengers in a typical 1991 automobile results in an energy intensity of 1442 Btu per passenger mile.

Total energy consumption by passenger cars is a function of vehicle miles traveled and the fuel economy of the mix of vehicles on the road. Fuel economy for passenger cars as a function of the automobile population is shown in Table 5.2.

Although average fuel economy has improved steadily, a decline in total fuel consumption has not been realized because of the significant growth in VMT. Total passenger VMT increased at an average annual rate of 2.6% between 1970 and 1992.[7] More recently, annual growth accelerated to 3.2% between 1982 and 1992. The average occupancy calculated as person miles per vehicle miles declined from 1.9 in 1977 to 1.6 in 1990.[7]

Statistics for two-axle trucks, which include vehicles larger than those shown in Table 5.2, reveal similar trends. Table 5.3 lists information about two-axle trucks. Fuel economy for trucks is significantly less than the fuel economy of passenger cars. In 1992, fuel economy for the fleet of trucks on the road was one-third less than for passenger cars. Registrations have increased from 14.2 million vehicles in 1970 to 39.5 million vehicles in 1992.[9] The average annual percentage change in registrations for trucks is 4.8% between 1970 and 1992, compared with 2.2% for passenger vehicles during the same period.[9] Table 5.4 shows that VMT have increased more rapidly for trucks than for passenger vehicles. This trend is reducing the combined fuel economy for passenger cars and light trucks.

Fuel economy is a function of new vehicle design, driving behavior, vehicle maintenance, and age of the vehicle. The

TABLE 5.1. PASSENGER TRAVEL AND ENERGY USE IN THE UNITED STATES, 1991

Transport Mode	Vehicle Miles (millions)	Passenger Miles (millions)	Persons per Vehicle	Btu per Passenger Mile	Energy Use (trillion Btu)
Automobiles	1,533,552	2,453,683	1.6	3,604	8,845
Personal Trucks	299,984	449,976	1.5	5,854	2,634
Motorcycles	9,178	12,849	1.4	1,782	23
Buses					
Transit	2,182	21,150	9.7	3,811	81
Intercity	1,013	23,500	23.2	962	23
School	4,300	83,300	19.6	848	71
Air	7,772	350,685	45.1	4,739	1,662
Rail	1,082	24,815	22.9	3,192	250

Source: Ref. 7.

TABLE 5.2. STATISTICS FOR PASSENGER CARS

Year	Registrations (thousands)	VMT (millions)	Fuel Use (million gallons)	Fuel Economy (miles per gallon)
1970	89,244	916,700	67,820	13.5
1976	110,189	1,078,215	79,693	13.5
1982	123,902	1,166,256	70,062	16.7
1988	141,252	1,429,579	71,949	19.9
1989	143,026	1,477,769	72,749	20.3
1990	143,550	1,515,370	72,435	20.9
1991	142,569	1,533,552	70,692	21.7
1992	144,213	1,595,438	73,851	21.6
	Average annual percentage change			
1970–1992	2.2%	2.6%	0.4%	2.2%
1982–1992	1.5%	3.2%	0.5%	2.6%

Source: Ref. 7.

TABLE 5.3. STATISTICS FOR TWO-AXLE, FOUR-TIRE TRUCKS

Year	Registrations (thousands)	VMT (millions)	Fuel Use (million gallons)	Fuel Economy (miles per gallon)
1970	14,211	123,286	12,313	10.0
1976	22,301	225,834	20,164	11.2
1982	29,792	306,141	23,845	12.8
1988	37,096	439,496	32,803	13.4
1989	37,918	454,339	33,005	13.8
1990	38,864	466,092	32,937	14.2
1991	39,067	472,848	32,531	14.5
1992	39,533	476,587	33,139	14.4
	Average annual percentage change			
1970–92	4.8%	6.3%	4.5%	1.7%
1982–92	2.9%	4.5%	3.3%	1.2%

Source: Ref. 10.

TABLE 5.4. HIGHWAY VEHICLE MILES TRAVELED (IN MILLIONS) BY MODE

Year	Passenger Cars	Percent of Total	Two-Axle, Four-Tire Trucks	Percent of Total	Total Highway Vehicles
1975	1,033,950	78%	200,700	15%	1,327,664
1980	1,111,596	73%	290,935	19%	1,527,295
1985	1,260,565	71%	373,072	21%	1,774,179
1992	1,595,438	71%	476,587	21%	2,239,828

Total highway vehicles includes motorcycles, other single-unit trucks, combination trucks, and buses.
Source: Ref. 10.

Fuel Economy Guide published by the DOE lists estimates of miles per gallon for each vehicle available for the new model year. The fuel economy estimates are based on results of tests required by the EPA. Vehicles are tested in a controlled laboratory using a dynamometer. City and highway tests are conducted, which account for road and aerodynamic forces. The city test simulates a 7.5-mile, stop-and-go trip with an average speed of 20 mph. The trip lasts 23 minutes and includes 18 stops. Approximately 18% of the time is spent idling, which represents the driver waiting at a traffic light or rush-hour traffic conditions. Both cold and hot starts are used. For the highway fuel economy estimate, a mixture of noncity driving segments are simulated. The test covers 10 miles with an average speed of 48 mph. The test is run from a hot start and has little idling time and no stops except at the end of the test cycle.

The fuel economy is computed from emissions data for hydrocarbons (HC), carbon dioxide (CO_2), and carbon monoxide (CO). A carbon balance is used to determine the gasoline consumed during the test cycle. The combined fuel economy (FE_{comb}) is calculated from a weighted average of the city and highway fuel economy based on the following equation:

$$FE_{comb} = \frac{1}{\left[\left(\frac{0.55}{\text{City FE}}\right) + \left(\frac{0.45}{\text{Hwy FE}}\right)\right]}$$

The values published in the *Fuel Economy Guide* are adjusted to account for lower actual in-use fuel economy performance compared to the EPA test procedure. The laboratory results are adjusted downward according to a study conducted by EPA which measured actual on-road fuel economy realized by the average driver. The laboratory city value is multiplied by 0.9, and the highway value is multiple by 0.78. For example, a test result of 35 mpg would translate to approximately a 30-mpg adjusted value.

Sales-weighted corporate average fuel economy (CAFE) is based on unadjusted laboratory test data. The CAFE standards are generated by a process established by law in 1975, before EPA began to make adjustments. Consequently, a discrepancy exists between sales-weighted average CAFE values and fuel economy estimates reported in the *Fuel Economy Guide*. Table 5.5 contrasts CAFE standards for automobiles with sales-weighted combined fuel economy estimates for automobiles and light trucks as measured by EPA test procedures.

The sales-weighted average fuel economy for automobiles manufactured and sold by the U.S. automotive industry corresponds closely to the average CAFE standard

$$\text{CAFE} = \frac{\Sigma N_i}{\Sigma\left[\frac{N_i}{FE_{\text{comb, i}}}\right]}$$

where N_i is the number of i model cars sold with a fuel economy of $FE_{\text{comb, i}}$.

Light-duty truck sales in the United States have increased dramatically, contributing to an increase in fuel consumption. Light-truck (less than 14,000 lbs) sales captured 39% of the new vehicle market (passenger cars and light trucks) in 1993. In 1981, light-truck sales accounted for only 19%.[11] This trend is expected to continue and has been estimated to reach 50% within 15 years.[12]

Figure 5.1 shows that the combined sales-weighted fuel economy for passenger vehicles and light trucks in 1993 was 25.4 mpg because the fuel economy for light trucks was only 20.8 mpg versus 28.3 mpg for passenger vehicles. As indicated previously, these values overstate actual fuel economy performance.

Table 5.6 presents new-car fuel economy data from selected countries between 1975 and 1990. Caution should be used when comparing these data because of differences in test cycles and definitions for classifying automobiles (e.g., light-duty trucks versus passenger cars). Noting this caveat, these data indicate that France and Denmark have the most fuel-efficient automobiles among the countries studied and that the United States has the least efficient vehicles. The United States also has the highest annual VMT per vehicle. This disparity is consistent with other patterns of resource use and waste generation.[13]

5.1.3 Emissions

The primary air pollutants from the use stage of the automobile life cycle include CO, nitrogen oxides (NO_x), particulate matter less than 10 microns (PM-10), sulfur dioxide (SO_2), volatile organic compounds (VOC), and lead. Large quantities of carbon dioxide, which is a greenhouse gas, also are released. Sources of air pollution from automobiles can be classified into four categories: 1) exhaust

TABLE 5.5. CAFE AND ESTIMATED SALES-WEIGHTED FUEL ECONOMY FOR AUTOMOBILES AND LIGHT TRUCKS

	Automobiles				Light Trucks[a]			
		Sales-Weighted Estimated mpg				Sales-Weighted Estimated mpg		
Year	CAFE	Domestic	Import	Combined	CAFE	Domestic	Import	Combined
1978	18.0	18.7	27.3	19.9				
1979	19.0	19.3	26.1	20.3	17.2	17.7	20.8	18.2
1980	20.0	22.6	29.6	24.3		16.8	24.3	18.5
1981	22.0	24.2	31.5	25.9		18.3	27.4	20.1
1982	24.0	25.0	31.1	26.6	17.5	19.2	27.0	20.5
1983	26.0	24.4	32.4	26.4	19.0	19.6	27.1	20.7
1984	27.0	25.5	32.0	26.9	20.0	19.3	26.7	20.6
1985	27.5	26.3	31.5	27.6	19.5	19.6	26.5	20.7
1986	26.0	26.9	31.6	28.2	20.0	19.9	25.9	21.5
1987	26.0	27.0	31.2	28.5	20.5	20.5	25.2	21.7
1988	26.0	27.4	31.5	28.8	20.5	20.6	24.6	21.3
1989	26.5	27.2	30.8	28.4	20.5	20.4	23.5	20.9
1990	27.5	26.9	29.9	28.0	20.0	20.3	23.0	20.7
1991	27.5	27.3	30.0	28.3	20.2	20.9	23.0	21.3
1992	27.5	27.1	29.1	27.9	20.2	20.5	22.4	20.8
1993	27.5	27.7	29.5	28.3	20.4	20.4	22.6	20.8

[a] Two- and four-wheel drive; gross vehicle weight ≤ 6000 lbs for 1979, ≤ 8500 lbs subsequently.
Source: Ref. 9.

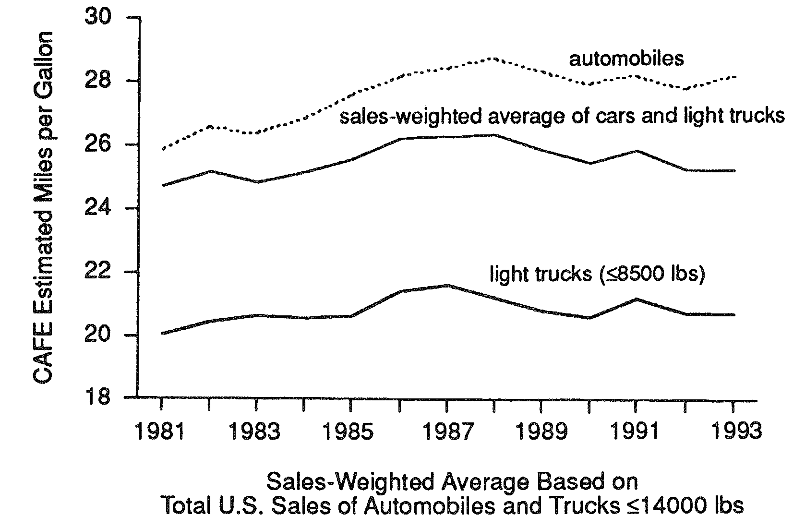


Fig. 5.1 Sales-weighted CAFE estimates, automobiles and light trucks. (Source: Refs. 9 and 11.)

TABLE 5.6. NEW GASOLINE AUTOMOBILE FUEL ECONOMY (MILES PER GALLON) FOR SELECTED COUNTRIES

Year	Japan	France	Italy	Sweden	Norway	Denmark	West Germany	United States
1975	21.2	27.7			24.8	28.3		15.4
1980	28.2	30.4	28.4	26.3	26.7		26.7	22.6
1985	29.2	35.1	32.9	27.8	30.3	35.3	32.0	25.1
1990	27.1	36.3		28.5	31.8	35.7	30.0	25.3

Source: Ref. 7.

emissions, 2) evaporative emissions, 3) refueling losses, and 4) crankcase losses. Air pollution from automobiles during operation largely results from combustion of fossil fuel. Carbon monoxide is a product of incomplete combustion. Although most hydrocarbons in fuel are combusted completely, forming carbon dioxide and water, some remain unburned or react to form new hydrocarbons. NO_x is produced from the oxidation of nitrogen, a reaction that is enhanced at higher temperatures. Gasoline consisting of sulfur impurities leads to SO_2 production. PM-10 is a major pollutant from diesel engines.

Additional pollution sources include evaporative emissions of hydrocarbons from engines and fuel systems when automobiles are not running. These emissions are classified as diurnal or "breathing" losses, transitory trip-end or "hot soak" losses, continuous resting losses from porous tubing or leaks of liquid fuel, and refueling emissions.[14] Evaporative emissions from sources other than the tailpipe are referred to as running loss emissions when the engine is in operation. Crankcase emissions of hydrocarbons, or blowby losses, originate from disabled or disconnected hoses.

Automobiles are responsible for a significant fraction of many of the six pollutants with National Ambient Air Quality Standards (NAAQS) established by EPA. A summary of their effects is provided in Table 5.7.

Table 5.8 shows the total national emissions of these air pollutants from highway vehicles. This table also shows the percentage contribution made by highway vehicles to total emissions from all sources, including aircraft, railroads, vessels, other off-highway equipment, stationary source fuel combustion, industrial processes, and waste disposal and recycling. Highway vehicles contribute significantly to total national emissions of all these pollutants except sulfur dioxide.

TABLE 5.7. EFFECTS OF NAAQS POLLUTANTS

Pollutant	Health Effects
CO	Reduces delivery of oxygen to the body, which is particularly serious for those with cardiovascular disease; causes impairment of function in healthy people
NO_x	In high concentrations, irritates lungs and lowers resistance to respiratory infection; an important precursor to ozone and acid precipitation which can damage sensitive ecosystems
VOC	Results in ozone which can damage lung tissue, reduces lung function, and causes irritation (these effects occur even at low levels in healthy people who engage in moderate exercise); also causes ecosystem degradation, mainly through damaging foliage
PM-10	In high concentrations aggravates existing respiratory and cardiovascular disease, alters the immune system, can be carcinogenic, and causes lung damage
SO_2	Major contributor to acid rain; degrades lung function and lowers lung defenses while aggravating existing respiratory disease
Lead	Accumulates in the body and affects kidneys, liver, and nervous system; causes neurological impairments

As stated previously, PM-10 is particulate matter less than 10 microns. A miscellaneous category consisting of agriculture, other combustion and fugitive dust from roads and other sources accounted for 88% of PM-10 emissions.[15] By 1994, unleaded gasoline sales accounted for 99% of the gasoline market. Under the CAAA, leaded gasoline was prohibited for use in highway vehicles after December 31, 1995. The contribution of highway vehicles to total emissions in urban areas is significantly higher: 74% of CO, 46% of NO_x, and 33% of VOCs.[16]

TABLE 5.8. TOTAL NATIONAL EMISSIONS (MILLIONS OF SHORT TONS), 1994

Sector	CO	NO_x	VOC	SO_2	PM-10	Lead
Highway Vehicles	61.1	7.5	6.3	0.3	0.3	0.0014
Total National	98.0	23.6	23.2	21.1	45.4	0.0050
Percent of Total	62.3%	31.9%	27.2%	1.4%	0.7%	28.0%

CO = Carbon monoxide.
NO_x = Nitrogen oxides.
VOC = Volatile organic compounds.
SO_2 = Sulfur dioxide.
PM-10 = Particulate matter less than 10 microns.
Source: Ref. 15.

The NAAQS in effect in 1993 are reported in Table 5.9. Ground-level ozone is a primary constituent of smog and is the major urban air quality problem. Ozone is formed by the reaction between NO_x and VOC in the presence of sunlight. Emissions from automobiles are partially responsible for 50 (22 serious and 28 moderate) nonattainment areas for ozone and 41 (2 serious and 39 moderate) nonattainment areas for CO, which were designated as of mid-1995. The automotive industry has made substantial progress in reducing vehicle emissions, which has contributed toward a decrease in the number of air quality exceedances. Improvements in air quality have been achieved despite increases in VMT.

Combustion of gasoline by automobiles is responsible for a significant fraction of greenhouse gas emissions in the United States. Fuel combustion associated with automobiles and light-duty trucks accounted for 19% of total U.S. CO_2 emissions in 1991.[7]

The EPA has established emission standards for three primary pollutants from gasoline-powered motor vehicles and engines: HC, CO, and NO_x. The EPA also established an additional particulate standard for diesel-powered vehicles. Tier 1 standards for passenger vehicles are 0.25 g/mi for HC, 3.4 g/mi for CO, and 0.4 g/mi for NO_x.

The OEMs have achieved a significant reduction in emissions from new vehicles, which have been driven by more stringent exhaust emissions standards set forth by EPA under the Clean Air Act (CAA) and California Air Resources Board (CARB). Figure 5.2 shows that emission standards have been reduced by 96% for CO and HC and 90% for NO_x during the last 28 years.

TABLE 5.9. NATIONAL AMBIENT AIR QUALITY STANDARDS, 1993

Pollutant	Type of Average	Standard Concentration
CO	8-hour	9 ppm
	1-hour	35 ppm
Pb	maximum quarterly average	1.5 μg/m³
NO_2	annual arithmetic mean	0.053 ppm
Ozone	maximum daily 1-hour average	0.12 ppm
PM-10	annual arithmetic mean	50 μg/m³
	24-hour	150 μg/m³
SO_2	annual arithmetic mean	80 μg/m³
	24-hour	365 μg/m³

Source: Ref. 17.

More stringent requirements relative to the current CAA requirements for conventional vehicles were established by CARB, as shown in Table 5.10.

Gasoline, alcohol, compressed natural gas, and liquefied petroleum gas with fuel and vehicle improvements are projected as capable of meeting the low-emission vehicle standards.

Several studies demonstrate that vehicle emissions over an operating lifetime are significantly greater than those projected from new-car certification standards. Emissions and fuel consumption for the average passenger car on the road in 1995 are provided by EPA in Table 5.11.

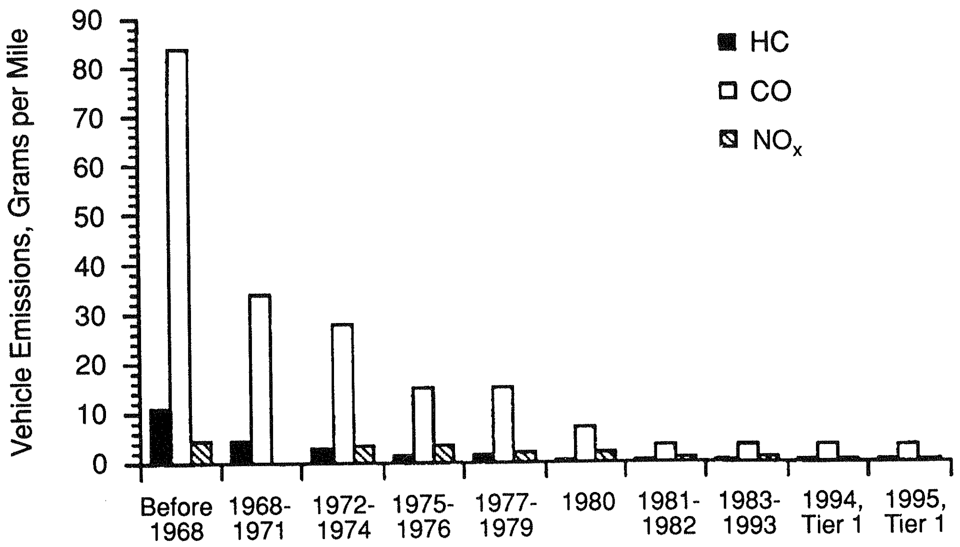


Fig. 5.2 Passenger car exhaust emissions standards in the United States. (Source: Ref. 18.)

TABLE 5.10. AUTOMOBILE EXHAUST EMISSION STANDARDS UNDER CARB

Air Emissions	Conventional Vehicle (CV)	Transitional Low Emission Vehicle (TLEV)	Ultra Low Emission Vehicle (ULEV)	Zero Emission Vehicle (ZEV)
HC	0.25	0.125	0.04	0
CO	3.40	3.40	1.70	0
NO_x	0.40	0.40	0.20	0

TABLE 5.11. ANNUAL EMISSIONS AND FUEL CONSUMPTION FOR AVERAGE IN-USE PASSENGER CAR, 1995

	Amount per Mile	Annual Amount
Hydrocarbons	3.1 g	75 lb
Carbon Monoxide	23.0 g	557 lb
Nitrogen Oxides	1.6 g	39 lb
Carbon Dioxide	0.9 lb	10,000 lb
Gasoline	0.05 gal	550 gal

Average annual miles driven assumed to be 11,000.
Based on standard EPA emission models, which assume an average properly maintained car on the road in 1995 operating on typical gasoline in normal summer weather.
Fuel consumption based on 21.6 mpg for average in-use passenger car.
Source: Ref. 19.

These emissions greatly exceed the EPA Federal Emissions Control Requirements for 1995 new vehicles as shown in Figure 5.3. Emissions factors (g/mi) for light trucks are substantially higher than for passenger vehicles.[20] Consequently, the market shift to light trucks will lead to a greater degradation in air quality while increasing fuel consumption.

Preliminary data from An *et al.*[21] indicate that average exhaust emission factors over a vehicle lifetime for late-1980s and early-1990s light-duty vehicles are approximately 16 g/mi for CO, 0.9 g/mi for HC, and 1.4 g/mi for NO_x. Thus, an average light-duty vehicle will emit approximately 2100 kg of CO, 120 kg of HC, and 190 kg of NO_x during its lifetime. High-power operation, stabilized running, and cold/hot starts each account for approximately 30 to 37% of CO emissions. For HC emissions, stabilized running and cold start dominate, with approximately 85% of the total. Stabilized running and high-power operation dominate NO_x emissions, accounting for approximately 75% of the total. Thus, hot-stabilized operation is the major source for all emissions.

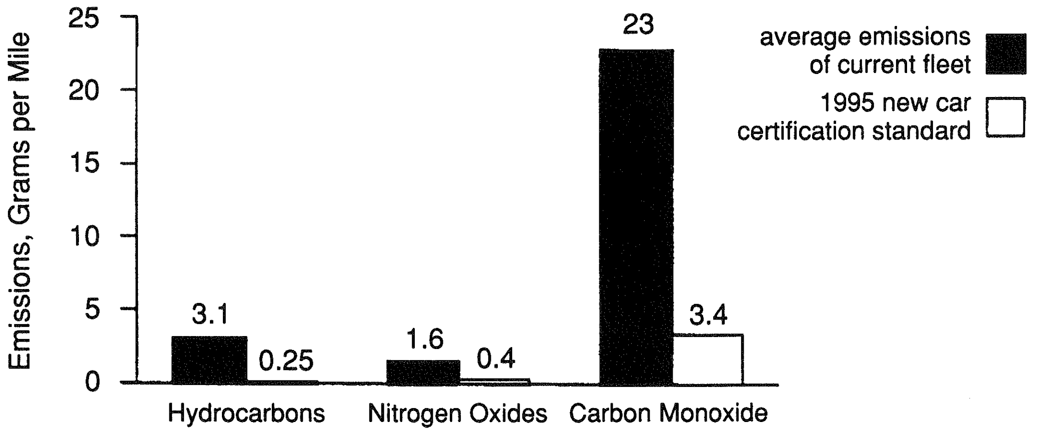


Fig. 5.3 Current fleet emissions vs. 1995 standards for new cars. (Source: Ref. 19.)

Greenhouse gas emissions from automobile use are dominated by carbon dioxide with trace releases of nitrous oxide and chlorofluorocarbons (CFCs). In 1992, the U.S. transportation sector produced 424.9 million metric tons of carbon dioxide from fossil energy consumption, which accounted for 32% of the 1317.2 million metric tons of carbon dioxide for all energy consumption sectors (residential, commercial, industrial, and transportation).[7] Gasoline use produced 259.7 million metric tons of carbon dioxide. Automobile greenhouse gas emissions from combustion of standard gasoline in an average vehicle are 344.5 g/mi of CO_2 equivalents.[22]

The Intergovernmental Panel on Climate Change (IPCC) recently released a draft report to advise parties of the United Nations Convention on Climate Change. This peer-reviewed report concluded that "a pattern of climatic response to human activities is identifiable in the climatological record," and the 0.3 to 0.6°C observed average increase in global temperature "is unlikely to be entirely due to natural causes." A 1.5 to 3.5°C average rise in average global temperature is projected for the next century, based on an expected doubling of greenhouse gas levels during that period.[23]

5.1.4 Vehicle Maintenance Impacts

Vehicle maintenance and service operations contribute significantly to the environmental impact of automobile use. More than 117,000 automobile repair shops exist in the United States.[11] These shops, along with do-it-yourself repairers, generate waste products such as brake linings, refuse metal and rubber parts, air and oil filters, lead-acid batteries, tires, used engine oil, antifreeze, hydraulic fluids, and CFCs from air conditioning systems. Approximately 250 million gallons of used engine oil are discharged to the environment each year, often in sewers, storm drains, and landfills.[24] Used oil runoff is difficult to treat and is a major contributor to pollution of the nation's waterways.

Used tires are a significant solid waste burden. Two to three billion tires currently are stockpiled in the United States. More than 240 million tires are scrapped each year, approximately 37% of which are burned for energy, reused, or recycled.[25] Used tires are becoming increasingly difficult to landfill. Some states entirely ban tire disposal; others ban only disposal of tires in landfills.[26]

Vehicle repair and maintenance processes also generate wastes such as organic solvents, paint sludges, and alkalis. Hazardous organic solvents used for parts cleaning, such as naphtha, chlorinated solvents, and mineral spirits, can evaporate or contaminate groundwater if landfilled or dumped.[27] Citrus-based solvents are a viable substitute for some organics.

Car washing is another aspect of continuing vehicle maintenance that adversely impacts the environment. A survey at a washing facility in Ann Arbor indicated a total electricity bill of $35,000 for 100,000 cars washed yearly. Assuming a rate of $0.0995/kWh, washing each car consumes 3.52 kWh of electricity, or approximately 12×10^3 Btu. In addition, 75 gallons of water are used for each car washed.[28]

5.1.5 Other Environmental Externalities

Natural habitat and biodiversity loss are environmental externalities that partially result from the extensive infrastructure required to support automobile use and goods transport in the United States. The United States has 3.9 million miles of roads and highways. The total surface area covered by roads, highways, parking lots, and garages in the United States is more than that devoted to housing.[29] The conversion of land to accommodate automobile infrastructure threatens the integrity of many wetlands, natural habitats, and populations of flora and fauna. Most major highways were constructed during the 1950s and 1960s, when knowledge of sound ecosystem management was limited. Today, highways and the often accompanying residential development contribute significantly to the primary cause of species extinction—fragmentation of natural habitats.

Concrete is composed of four major components: portland cement, sand, crushed stone, and water. The most energy-intensive component is cement, which is produced from lime (limestone, marl, and chalk), silica (clay, sand, and shale), alumina (bauxite), ferric oxide, and gypsum.

Cement production accounts for 0.6% of total U.S. energy consumption. Concrete production and handling requires 6.4×10^6 Btu/ton; 92.4% of this energy can be attributed to cement production and handling.[30] Additionally, cement production accounts for more than 8% of CO_2 emissions from all human activities worldwide.[31] Approximately 1.2 tons of CO_2 are emitted per ton of cement.[30] Other emissions from cement kilns include hydrogen sulfide, sulfur dioxide, nitrogen oxides, and sulfuric acid.

Noise and vibration resulting from automobile use have adverse impacts on the quality of life for residents living near highways. Unfortunately, noise from highway traffic cannot be fully mitigated by sound barriers. Vibration is not remedied by barriers and can cause serious structural damage to nearby structures. Estimating property value depreciation resulting from highway noise is difficult because other variables related to highway use (i.e., aesthetics, pollution, and safety issues) also affect property values and may be closely correlated with noise levels.

5.2 Public Policy and Legislation

The environmental and societal burdens of automobile use have received increased scrutiny as the environmental problems associated with automobile use have worsened. Policymakers and Congress realize the importance placed on environmental quality by liberal and conservative voters, and they are closely examining the true magnitude of the externalities associated with automobile use. However, the ability of policy-makers to experiment with different policy options to reduce these externalities is severely limited by the current fiscal situation. Public dissatisfaction with taxes and the federal budget deficit has spurred legislators to reevaluate current expenditures on virtually every federal policy, program, and agency, including those that address the environmental impacts of automobile use. Policies that do not meet tests of economic efficiency may be eliminated in favor of more cost-effective alternatives. Other policy options, although economically sound, may be rejected because they lack political viability. This section will summarize existing legislation and policy options at the federal level that address the most significant externalities of automobile use—fuel consumption, greenhouse gas and other pollutant emissions and their associated impacts, and congestion. These policies have the greatest potential to reduce the environmental impacts of the automotive system by influencing the behavior of consumers and OEMs.

5.2.1 Fuel Consumption

The United States accounted for 25% of the world's total petroleum consumption in 1992,[7] and the transportation sector is the most significant consumer of oil within the United States. Gasoline for transportation accounted for 40% of total U.S. petroleum consumption in 1992.[7] Table 5.12 shows the distribution of transportation energy use by mode, with automobiles and light trucks constituting 58.8% of total consumption in 1992.

The U.S. demand for petroleum is met by a combination of domestically produced and imported oil. The dramatic increase in oil prices resulting from the Arab oil embargo of 1973 illustrated how the importation of petroleum from politically sensitive regions of the world can threaten U.S. national security interests.

TABLE 5.12. TRANSPORTATION ENERGY USE BY MODE, 1992

Mode	% of Total	Mode	% of Total
Highway		Off-Highway	
Automobiles	40.1	Farming/Construction	2.9
Light Trucks[a]	18.7	Air	8.5
Other Trucks	14.7	Water	7.1
Buses	0.8	Pipeline	3.7
		Rail	2.2

a Two-axle, four-wheel trucks.
Source: Ref. 7.

Federal government expenditures to maintain a military presence in the Persian Gulf region and a national strategic reserve of petroleum are enormous and should be considered an external cost of gasoline consumption. Resources for the Future estimated $15 to $54 billion for 1989 military expenditures to protect U.S. petroleum interests in the Persian Gulf. The cost of Desert Storm, a full military engagement, was an estimated $1.4 billion per day.[32] Despite national security concerns, imports have increased as a percentage of total consumption since the price shocks of the 1970s. Production costs in the United States are increasing as domestic reserves fall.

Policies aimed at reducing U.S. energy consumption are best understood by broadly reviewing drivers of fossil fuel consumption by light-duty vehicles. One of the most important drivers of U.S. demand for gasoline is its low per-gallon price. Taxes on gasoline have always been considerably lower in the United States relative to other industrialized countries, and the real price of gasoline has fallen, as Table 5.13 shows.

TABLE 5.13. GASOLINE PRICES PER GALLON IN CONSTANT 1990 DOLLARS

Country	1982	1992
Japan	3.52	3.52
France	3.47	3.44
Italy	3.90	4.48
Sweden	3.25	3.98
United Kingdom	3.28	3.05
West Germany	2.94	3.58
Canada	1.85	1.96
United States	1.79	1.00

Source: Ref. 33.

Gas and oil accounted for only 13.1% of the total cost of operating a car in 1992, compared with 22.6% in 1985.[34] Recent market surveys find that consumers who contemplate new-vehicle purchases rate fuel economy as a very low priority behind price, safety, styling, performance, and other amenities.

Light-duty VMT also is a critical component in characterizing and forecasting fuel use in the transportation sector. Various forecasts assert that highway VMT will grow at an annual rate of approximately 2% during the period of years from 1990 to 2010, which is a decrease from the 1970 to 1990 annual rate of almost 4%.[34] Although future vehicle energy consumption is a function of improvements in average vehicle fuel efficiency, penetration of alternative fuel substitutes, and changes in consumer preferences, the trend will be continuing increases in transportation petroleum use in step with absolute increases in VMT.

5.2.2 CAFE

In the wake of the OPEC oil embargo and a tripling of world oil prices in the early 1970s, Congress passed the Energy Policy and Conservation Act of 1975. The Act aimed to reduce U.S. consumption of fossil fuels by establishing minimum corporate average fuel economy (CAFE) standards for cars and light trucks. CAFE standards for each producer's vehicle fleet are calculated for car and light truck categories. Manufacturers incur penalties of $50 per vehicle for each 1-mpg deficiency, although credits for surpassing the standards can be carried backward or forward three years. Penalties are passed to consumers in the form of higher vehicle prices. The CAFE standards for automobiles were set at 18 mpg for the 1978 model year and 27.5 mpg for the 1985 model year. CAFE is a harmonic weighted fleet average based on EPA city-highway ratings, which assumes that the mileage accumulated by all models is equal.

The CAFE standards for light trucks have lagged behind automobile CAFE standards considerably. The automobile standard of 27.5 mpg was established for 1985 and remains in effect. The light-truck standard climbed from 14 mpg in 1980 but has stagnated at 20.5 mpg since then. Congress gave the Department of Transportation the power to set light-truck CAFE standards. Critics of the light-truck standard argue that the same standards should apply to automobiles and light trucks because the latter have assumed a large part of the market for new vehicle sales. In addition, light trucks often are used for the same functions as passenger cars.

Actual average fuel economy for light trucks is currently 20.4 mpg, whereas that of the automobile fleet peaked at 28.6 mpg in 1988 and has fallen to 28.2 mpg today. The disparity between automobile and light-truck CAFE standards and actual fuel efficiency is growing in importance because of the tremendous growth in sales of sport-utility vehicles, minivans, and pickups. The increasing popularity of light trucks will continue to result in a loss of fuel efficiency in the overall vehicle fleet. The National Highway Traffic Safety Administration (NHTSA), the agency that administers light-truck standards, has proposed raising standards for the 1998 model year. The Big Three OEMs that oppose the increase suggest that an increase would abet a foray into the light-truck market by Japanese OEMs, which now sell a higher proportion of more fuel-efficient four- and six-cylinder trucks.

Two decades after the inception of the program, controversy continues to surround the effectiveness and economic efficiency of CAFE standards as an instrument to achieve reductions in light-vehicle petroleum consumption. The issues are whether CAFE has been a binding constraint for domestic manufacturers and whether it is an economically efficient policy for reducing fuel consumption. It is impossible to isolate the extent to which higher real-fuel prices in the 1970s would have pushed manufacturers and buyers toward greater efficiency in the absence of CAFE standards; therefore, analysis is difficult. The hope was that CAFE standards would force manufacturers to reduce weight and acceleration capability while improving technology, thus resulting in more fuel-efficient vehicles across the entire fleet.

The argument for CAFE standards is that they have been superior to fuel price in inducing improvements in fuel economy without the socially regressive distributive implications of a gasoline tax. Proponents of CAFE state that the standards have stimulated technological improvements such as front-wheel drive and fuel injection without compromising consumer tastes. The contention that CAFE is a constraint is based on the correlation between the standards and the fuel economy performance realized by manufacturers. Daniel Greene of Oak Ridge National Laboratory estimated that the CAFE performance of the Big Three manufacturers closely follows the fuel economy standards for a given year and that the standards have saved $103.4 billion in fuel during the period 1984 to 1989 in discounted 1990 dollars.[35]

Critics of CAFE contend that the standards aim at vehicles instead of the most important factor in fuel economy—drivers. When the price of gas is stable or falling, drivers have incentives to drive more miles and purchase less-fuel-efficient vehicles. CAFE addresses only new cars, which represent a relatively small percentage of the overall vehicle fleet. Thus, significant fleetwide improvements in fuel economy depend on sales and penetration of new vehicles. Higher vehicle prices resulting from CAFE costs may encourage consumers to retain their existing vehicles longer, slowing replacement of the vehicle stock. These old vehicles generally pollute more than new models. The median age of registered automobiles rose from six years in 1970 to more than eight years in 1990. Old cars typically are less fuel efficient than new cars.[36] CAFE standards do not address fuel consumption of old vehicles on the road. The main critique against continuing CAFE as an energy conservation policy contends that CAFE standards may have minimally constrained manufacturers before 1985 but failed to constrain them after gas prices began to fall in the mid-1980s. Seeking further incremental increases in fuel economy through CAFE is extremely costly. An estimate by economists Robert Crandall and Lester Lave[36] of the cost of a 10% improvement in fuel economy achieved through technology is $560 per car.

Table 5.14 summarizes findings from a National Research Council Committee on Fuel Economy of Automobiles and Light Trucks[37] on the limitations and merits of both CAFE standards and a market-based approach to promoting fuel conservation. This committee concluded that CAFE is increasingly at odds with market signals. Automobile manufacturers uniformly identified increasing fuel prices as a desirable alternative to the CAFE system. They emphasized that bringing the price of fuel in line with true societal costs would allow market pressure to provide appropriate incentives to consumers. Table 5.14 indicates that many of the key issues can be argued from both perspectives. Until society fully recognizes the value of fuel conservation actions by consumers, policy-makers and manufacturers will be limited in their effectiveness.

TABLE 5.14. MERITS AND LIMITATIONS OF CAFE STANDARDS AND INCREASED FUEL PRICES

CAFE Standards

Positive Features

- Technology forcing (forces manufacturers to introduce fuel conserving technology; strong incentive for manufacturers to provide both fuel economy and vehicle characteristics that consumers favor)
- Reduced vulnerability to increased oil prices
- Market prices (reduces the capacity of foreign oil suppliers to raise prices; reduces the demand for petroleum)

Drawbacks

- Dissonance between CAFE requirements and market signals (to the extent that improved fuel economy is achieved at the expense of other characteristics of the vehicle that the consumer values more, the market is being required to try to sell a product that does not reflect consumer demand)
- Competitive effects (full-line manufacturers must strain to comply, whereas small-car manufacturers comply with comparative ease)
- Attenuated impact on fuel consumption (does not provide an incentive for the use of a vehicle in a way that conserves fuel)
- Slow impact on fuel economy of fleet (affects only a portion of the fleet—the new vehicles sold in the years to which the standards apply)
- Gaming (invites gaming to exploit the system; manufacturers can adjust their cars to optimal fuel economy on the test cycle, which may not be optimal for real-world driving)
- Mix shifting (manufacturers may have to induce consumers to shift to smaller cars)
- Costs and benefits (marginal costs of requirements balance the marginal benefits; some agree the costs far exceed benefits, but others have found CAFE to be cost effective)

Increased Fuel Prices

Positive Features

- Encourages fuel conservation
- Impact on entire fleet
- Market reinforcement of societal goals (encourages consumers to weigh fuel economy more heavily among other attributes)
- Competitive effects (constrains full-line manufacturers only to the extent they are unable to provide vehicles with fuel economy of foreign manufacturers)
- Market efficiency (would not affect location of production operations)

Drawbacks

- Economic disruption (the size of the fuel price increase that would be required to achieve fuel savings equivalent to those demanded by aggressive CAFE standards may be substantial)
- Societal disruption (American society is based on mobility that low-cost fuel allows)
- Diminished pressure for technological change
- Mix shifting (shift toward smaller cars could have safety consequences)
- Impacts on manufacturers (demand for new vehicles would be reduced)

Source: Ref. 37.

DeCicco, John, and Ross[38] estimate that average new-car fuel economy in the year 2005 can be raised by 65%, from 28 to 46 mpg. Their estimate is based on adoption of more efficient technologies that are selected according to cost effectiveness. They estimate that fuel economy improvements would add $800 to the retail price of a car. Fuel savings of $2500 would be realized using current fuel prices over a 12-year vehicle life.

Economists argue a direct per-gallon tax on fuel would dampen demand for gasoline in a more economically efficient manner than CAFE standards, which directly regulate manufacturers' product decisions instead of VMT. A gas tax could achieve this by targeting a reduction in VMT, whereas CAFE standards encourage vehicle downsizing and an assumed decrease in safety.

5.2.3 Alternative Fuels

The drivers for alternative fuel use are the following:

- **Near term:** Improvement in air quality and reduction in greenhouse gas emissions. Air quality benefits depend on the nature of emission standards promulgated for alternative fuel vehicles and on the tradeoffs vehicle designers make among factors such as emissions, vehicle performance, and fuel economy. Near-term benefit in greenhouse gas emissions through alternative fuel use is expected to be small unless design decisions are controlled by strong incentives to reduce greenhouse gas emissions from the entire fuel cycle.[34]
- **Long term:** Need for alternative sources of energy as petroleum resources diminish. The integration of energy, security, and economic benefits from reducing oil use and imports is a major potential driver for the government.

The advantages and disadvantages of each alternative fuel are presented in the design section. The timing for complete transition to alternative fuel is too difficult to predict, although a rough estimate for the upper limit would be approximately 60 years, which is the projected adequacy of gasoline fuel reserves.

Several factors inhibit the introduction of alternative fuels into the marketplace: the entrenchment of gasoline in the light-duty vehicle market, the lack of supply infrastructure, mature vehicle technologies for most of the alternative fuels, and various cost and range problems. Liquid fuels are most compatible with current distribution systems and engines. All of the alternative fuels are less dense than gasoline and thus need a higher volume of fuel to achieve an equivalent range.[34]

Gasoline prices in the United States are now at or near their lowest levels since 1978, adjusted for inflation.[7] Gasoline costs two to three times more in the rest of the world. These low prices make it difficult for some alternative fuels to compete with gasoline. For example, the cost of compressed natural gas (CNG) and hydrogen is high relative to gasoline because of different storage requirements and engine fuel management requirements. Federal and state governments have initiated numerous important policies to move alternative fuels into the U.S. motor vehicle fleet.[34] These incentives include the following:

- California's Low-Emission Vehicle Program under the CAAA, which requires minimum sales of vehicles in different emissions categories, including the 2001 5% Zero-Emission Vehicle (ZEV) sales mandate and the 2003 10% sales mandate. (The 1998 mandate for 2% ZEV was rescinded by the California Air Resources Board in November 1995.) California emission standards should be reviewed with respect to life cycle emissions.
- Alternative fuel fleet requirements and tax incentives under the Energy Policy Act of 1992.
- Fuel economy credits to OEMs under the Alternative Motor Fuels Act of 1988; these credits may be applied toward meeting CAFE requirements by manufacturing alternative fuel vehicles. Because most OEMs can comply with current CAFE standards without a great deal of difficulty, the availability of the credits may have little effect unless CAFE requirements are raised.

However, fuel taxation policy does not appear to take rational account of alternative fuels' unique characteristics. The current policy taxes different fuels at different rates based on different environmental and energy security impacts and does not bear any relation to energy policy or environmental goals (e.g., ethanol, natural gas, and electricity benefit greatly from tax policy; propane and methanol generally are penalized). Accordingly, the Office of Technology Assessment[34] gave two recommendations for alternative fuel policy:

- Tax each alternative fuel at the same rate in dollars per Btu delivered to the vehicle, possibly with electricity rates being adjusted to account for energy lost at the power plant. The rate could be equal to or lower than current gasoline taxes, to reflect the government's desire to allow the market to decide or to favor alternative fuels over gasoline.
- Tax each alternative fuel at different rates that reflect evaluations of each fuel's nonmarket characteristics, e.g., energy security implications and environmental characteristics.

From a life cycle perspective, a more comprehensive economic instrument would also address the full fuel cycle energy and associated emissions. This approach would require some impact assessment method such as the Environmental Priority Strategy system for calculating environmental load units, which was developed by the Swedish Environmental Research Institute.[39] A more practical approach could develop a tax formula that would account for the major impact categories such as energy and greenhouse gas emissions using a weighting factor.

5.2.4 Speed Limits

Speed limits affect fuel economy and safety. The relationship between fuel economy and speed is indicated in Figure 5.4. Two separate Federal Highway Administration studies indicated that maximum fuel efficiency is achieved at speeds of 35 to 40 mph.[7] Fuel economy at 60 mph is 17.9% less than at the optimal 35 to 40 mph; at 70 mph, it is approximately 33% less.[7] Changing average highway speed from 55 mph to 70 mph would result in a fuel economy loss of 25.7%.

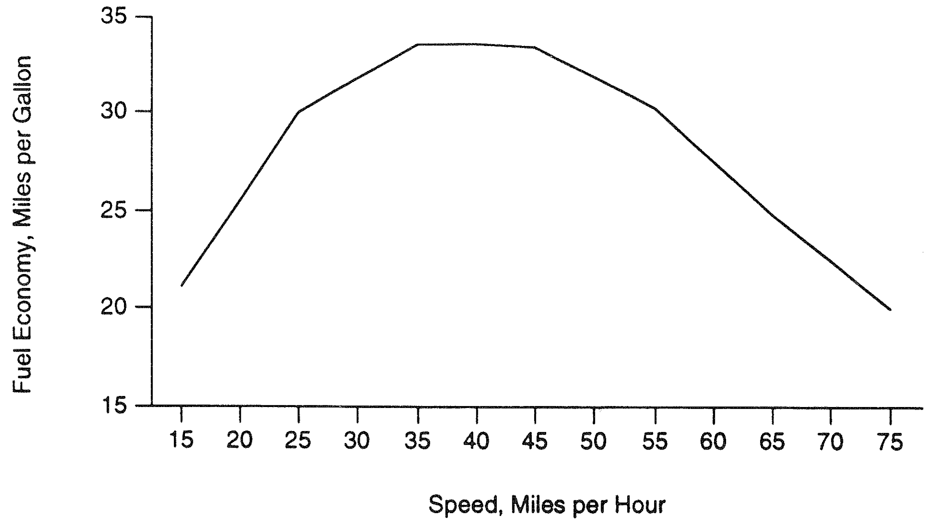


Fig. 5.4 Fuel economy and speed for 1984 vehicles. (Source: Ref. 7.)

Public Law 104-59, the National Highway System Designation Act of 1995, repealed federal laws mandating a 55-mph speed limit. This law permits states to set their own speed-limit standards.[40] Before a 55-mph speed limit was established in 1974, 30 states had top speed limits of 70 mph and 15 states had maximum speed limits of 75 mph. In 1987, Congress permitted states to set a maximum speed limit of 65 mph on interstate highways outside urban areas. Opponents of this law argued that it will result in an annual increase of approximately 4,700 traffic deaths and raise health care costs from injuries.[40]

5.2.5 Emissions

Although vehicle emissions have improved substantially during the past two decades, they remain a major contributor to CO, NO_x, CO_2, and VOC at a national level. Nonattainment of ozone standards in certain areas would suggest stricter emission standards for NO_x and VOC.

Recent evidence indicates that human activities, primarily through the burning of fossil fuels, are partially responsible for changes in global climate. Without drastic steps to reduce greenhouse gas emissions, most specialists predict that the average global temperature will increase 1 to 3.5°C during the next century.[23] The combustion of nonrenewable fossil fuel, which produces CO_2, may be one of the greatest threats facing sustainability of the automobile. The United

States has not been aggressive in curbing its CO_2 output. A strong policy is needed to address this potentially catastrophic effect.

The climate treaty signed at the Rio de Janeiro Earth Summit in June 1992 required that developed countries only "aim" to return their greenhouse emissions to 1990 levels by the year 2000.[41] President Clinton's Climate Change Action Plan indicated that fossil-fueled vehicles constitute the fastest-growing source of CO_2. The Clinton Administration admitted that its plan is not on track to meet the goal of 1990 emission levels by the year 2000.[41] The American Petroleum Institute is strongly opposed to extending the Rio de Janeiro treaty beyond voluntary targets.

A 1995 interim report by the IPCC concluded that the climate treaty in its present form would not lead to a stabilized atmosphere. The panel's report indicated that stabilization can be achieved only if emissions are reduced well below 1990 levels. To overcome competitiveness concerns, the Netherlands advocates international measures to control greenhouse gas emissions rather than regulations at the national level.

5.2.6 *Inspection and Maintenance*

One effective approach for reducing environmental burdens related to automobiles is to identify low-fuel-economy or highly polluting vehicles. Identified vehicles then can be repaired, if it is economical to improve their performance to an acceptable level, or retired if it is too costly to achieve desired performance.

Emissions data have shown that a small fraction of vehicles on the road are high emitters that greatly exceed emission standards. The EPA estimates that 10 to 30% of vehicles cause most air pollution problems.[42] Remote sensing studies, which are discussed below, indicate that the worst 10% of current vehicles in use contribute 50% or more of warm-running CO and HC automobile emissions.[43]

Inspection/Maintenance (I/M) programs are designed to check for proper functioning of emission control systems.[42] Although new vehicles are required to meet pollution standards, their performance can deteriorate significantly through use, often due to lack of proper maintenance. I/M programs periodically check vehicles to identify malfunctioning vehicles, perform required repairs, and discourage tampering with emission control devices. The EPA claims that I/M programs can reduce vehicle-related HC and CO emissions by 5% to more than 30%, and that comprehensive programs can achieve reductions of up to 10% in NO_x emissions.

I/M tests currently are conducted at government or privately run inspection stations. New technologies are being developed which may complement or possibly replace inspection stations. The future of these programs will depend on their costs, burdens imposed on vehicle owners, and their reliability. Two technologies for testing vehicle emissions are on-board diagnostic (OBD) systems and remote-sensing devices. The OBD systems use computers to monitor the performance of emission controls and send a signal to a dashboard indicator when emission controls malfunction.

Remote-sensing devices monitor vehicle emissions by passing an infrared beam across the road through vehicle exhaust.[44] Detectors analyze the infrared beam to measure the concentrations of CO and HC. A video camera may be used to identify the license number of high-emitting vehicles. One concern of this program is that recording a vehicle's location in time may be intrusive to the driver's privacy.

Another effective strategy for reducing pollutant emissions is to remove older, high-emitting vehicles from the road. Unocal Corporation, based in Southern California, formed Eco-Scrap Inc. to purchase old vehicles and thus reduce air pollution. For 1975 to 1981 vehicles, the owner is offered \$500; for vehicles older than 1975, the owner is offered \$600. The retired vehicles generate mobile source emission reduction credits for NO_x, CO, and HC. Since 1990, 10,200 vehicles have been retired, which prevented an estimated 800 tons of HC, 200 tons of NO_x, and 4700 tons of CO.[45]

5.3 Design Initiatives and Management Opportunities

A wide range of strategies and programs have been developed to reduce environmental burdens in the use phase of the vehicle life cycle. Improvements in fuel/energy efficiency and vehicle emissions range from incremental improvements in individual components such as catalysts to dramatic changes in vehicle system design such as hybrid vehicles. This section begins by addressing fuel economy improvement for a conventional internal combustion engine vehicle (ICEV). Existing and new improvement technologies related to engine performance, drivetrain performance, rolling resistance, aerodynamics, braking, accessories performance, and mass reduction are covered. Some of these technologies are relevant to alternative vehicle design. Emissions control technology and testing procedures for ICEVs then are evaluated. Alternative fuels represent another strategy for reducing vehicle emissions. The effectiveness of liquefied petroleum gas (LPG), natural gas, alcohol fuels, and hydrogen are examined. Finally, new and/or emerging alternative vehicle technologies such as electric vehicles, hybrids, and hypercars are evaluated, and an overview of the Partnership for a New Generation of Vehicles (PNGV) is provided.

5.3.1 *Fuel Economy*

The distribution of energy losses for a midsize sedan is shown in Figure 5.5.

Fuel consumption during the use phase accounts for approximately 90% of total energy use over the automobile life cycle (see Chapter 7). Therefore, increasing the fuel economy of current and future automobiles is the most successful way to reduce life cycle energy burden. Fuel economy can be reduced by factors such as improvement in traffic infrastructure, economic and policy changes, and technological improvements. Examples of improvement in traffic infrastructure are increased car occupancy (beyond 1.6 in the United States), reduced number of cars on the road, lifestyle changes, driver education, and downsizing. Examples of economic and policy factors include fuel taxes, fuel economy regulations, and feebates. The combination of these factors drives technological development for automobile fuel economy. In this section, the technological improvement of automobile fuel economy is described.

Figure 5.6 illustrates the energy losses for driving a typical spark ignition automobile.

Engine Performance

Thermodynamics and Combustion

The thermodynamics of a spark ignition engine approximately follows the Otto cycle. For an ideal Otto cycle, thermodynamic efficiency, defined as work output divided by heat supplied, is given by:

$$\eta_i = 1 - \frac{1}{r^{\gamma-1}}$$

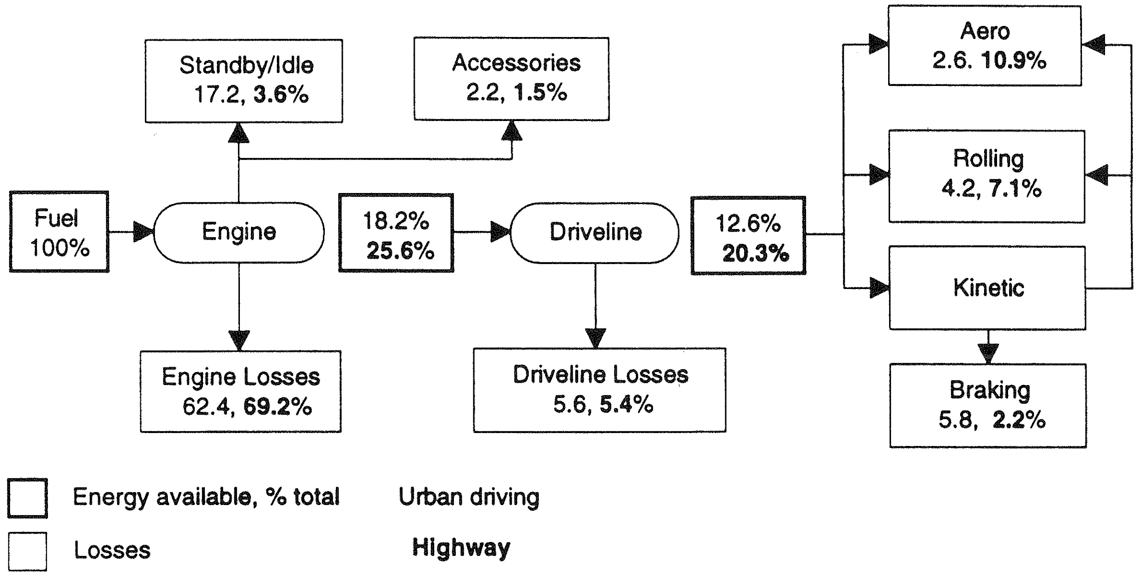


Fig. 5.5 Energy losses for current midsize sedan. (Source: Ref. 46.)

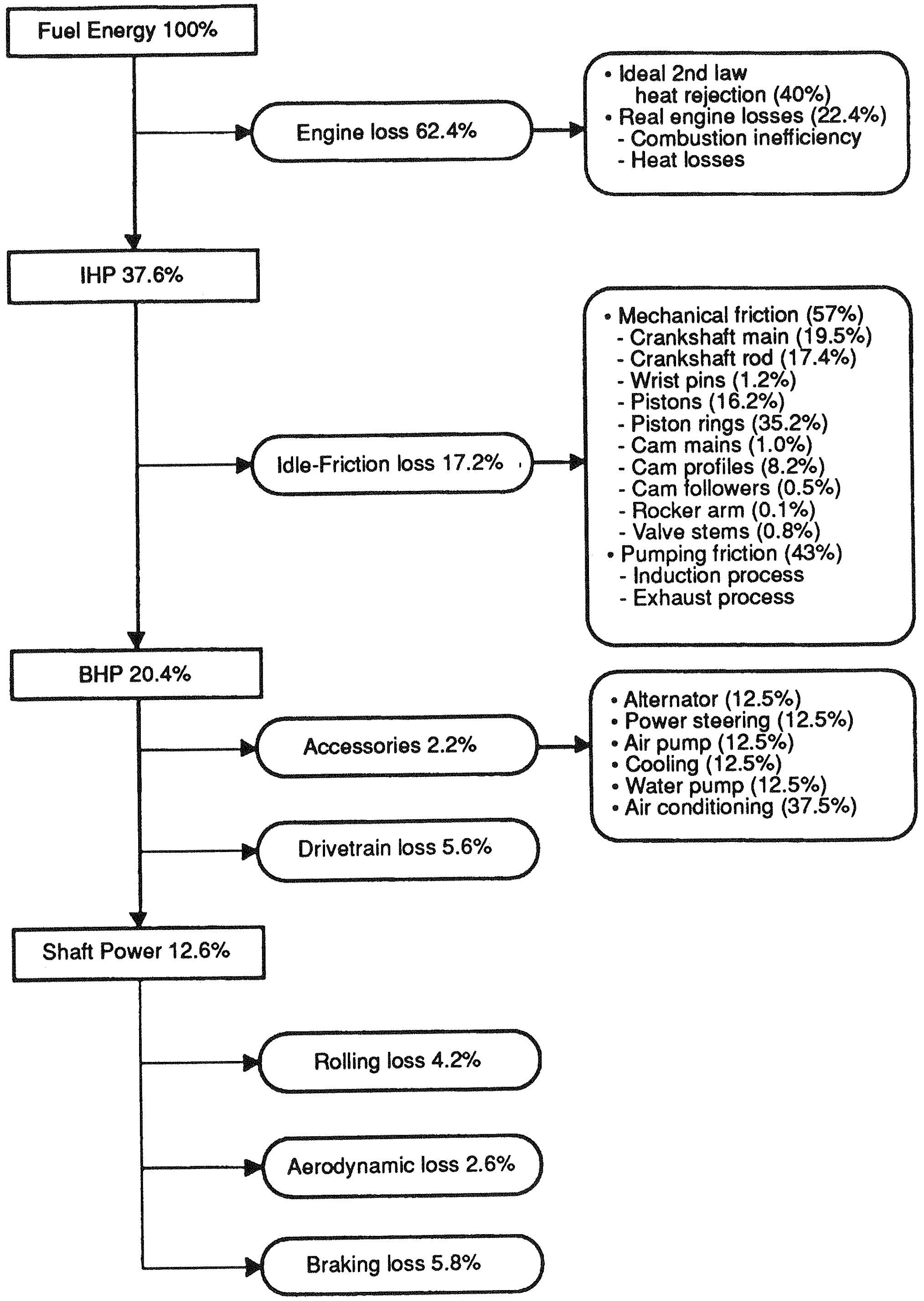


Fig. 5.6 Fuel energy loss (percent) in city driving for a typical spark ignition automobile. (Source: Refs. 46, 47, and 48.)

where $r = C_p/C_v = 1.4$ and γ = compression ratio (10 for a typical spark ignition engine).

Thus, a spark ignition engine following the ideal Otto cycle has a thermal efficiency of approximately 60%. This implies that 60% of the fuel energy is available as useful work, and the remaining 40% is unavoidably lost due to Second Law heat rejection. The current automobile engine uses only 37.6% of fuel energy during urban driving as indicated horsepower (IHP); 62.4% of fuel energy is dissipated as heat.[46] The difference in heat dissipated between a real engine and an ideal engine following the Otto cycle (approximately 22.4%) results from potentially recoverable losses such as combustion inefficiency, heat losses, and flow losses. In highway driving, energy loss from the engine is estimated to be 69.2%.[46]

Combustion efficiency for internal combustion engines is defined as the fraction of fuel energy combusted; it is a function of turbulence, charge density, and knock characteristics.[49,50] The degree of turbulence in the combustion chamber and in the flame front can be influenced by numerous factors, including the design of mixture inlet devices, the shape of the combustion chamber, and the use of piston movement to generate squish. Turbulence is a function of engine parameters, compression ratio, intake-air temperature, and engine speed. Excessive turbulence also can result in flame breakdown and quenching. Heat loss to the wall can result from several factors such as position of maximum heat release, outside temperature, and design of combustion chamber.

Valve timing denotes the sequence and duration of gas exchange within the combustion chamber relative to piston motion between top dead center (TDC) and bottom dead center (BDC). Valve timing affects most of the potentially recoverable losses as described below.[51]

Intake valve opening (IVO) marks the beginning of the intake process and is typically 10 to 25° before TDC. Engine performance is relatively insensitive to this timing point. Intake valve closing (IVC) occurs after BDC to provide more time for cylinder filling when the cylinder pressure is below intake manifold pressure (i.e., at high speed). Typical range is 40 to 60° after BDC. Delaying IVC causes volumetric efficiency to increase at high engine speeds but penalizes it at low engine speeds. Specific power loss due to late IVC is 0.42 to 0.65% per degree. Exhaust valve closing (EVC) marks the end of the exhaust stroke and valve overlap period. Typical range is 8 to 20° after TDC. EVC affects the burned gas fraction at idle and full load. Specific loss due to late EVC is 0.15 to 0.35% per degree. Exhaust valve opening (EVO) marks the beginning of the exhaust stroke and is timed such that cylinder pressure is reduced to near exhaust manifold pressure at or after BDC to minimize the pressure loss and maximize the volumetric efficiency. Typical range is 120 to 180° after TDC. Specific loss for early EVO is 0.07 to 0.12% per degree.

Engine Friction Loss

The PNGV reported that standby and idling account for 17.2% of the fuel energy loss in urban driving and 3.6% of the energy loss in highway driving.[46] Friction losses arise primarily from two factors: 1) moving parts within the engine (e.g., crankshaft, pistons, wrist pins, piston rings, cams, rocker arm, and valve stems), and 2) pumping losses concerned with induction of fresh charge and expulsion of exhaust gases. Pumping losses are a function of parameters such as engine and manifold pressure, wall friction, and valve timing. The total power dissipated as a result of friction (17.6% of fuel energy) is termed friction horsepower (FHP) and is the difference of indicated horsepower (IHP) and brake horsepower (BHP). Both FHP and BHP can be measured by electric dynamometer. The BHP is measured by the dynamometer while the engine is firing. The engine is then shut off, and the dynamometer is used as a motor to drive the engine under nearly the same operating conditions. The amount of power required to motor the engine is the estimated FHP.[49]

Friction losses can be reduced by many approaches such as using low viscosity oil or reducing mean pressure on piston rings, and by designing surfaces to maintain a thick fluid film between them during actual operating conditions. In cities and on congested highways, the engine is idling part of the time when the vehicle is not moving. Fuel consumption and emissions then become significant and could be reduced in numerous ways, such as storing energy in a recuperation system for engine restarting and modular engines with most cylinders disconnected at low-power settings.[52] Approximately three-quarters of daily trips are relatively short (less than 5 km) and thus are carried out in cold engine conditions where fuel consumption and pollutant emissions are high.[52]

The engine is the single most important factor governing fuel economy. Thus, engine modifications have the greatest potential for improving automobile energy efficiency. Together, engine thermodynamics and combustion and engine friction account for 80% and 73% of fuel energy loss in urban and highway driving, respectively. Because the use phase accounts for 90% of automobile life cycle energy (see Chapter 7), engine thermodynamics and friction are responsible for 66% (highway) to 72% (urban) of life cycle energy losses from conventional internal combustion engine automobiles. Some factors that can be used to reduce engine losses are described below:

Deceleration Fuel Reduction	Deceleration fuel reduction technology considers partial reduction in fuel flow during deceleration and is estimated to result in 1% fuel economy increase.[53,54]
Compression Ratio Increase	Increased compression ratio leads to higher thermal efficiency. However, too high a compression ratio (beyond 10:1) leads to knock, resulting in a decrease in power and thermal efficiency. Changes in engine design to compensate for the onset of knock can result in a 5 to 6% increase in compression ratio, resulting in a 1.3 to 2% increase in fuel economy.[53]
Fuel Injection	According to Energy and Environmental Analysis, Inc.,[55] multipoint fuel injection produces a 1.2 to 1.5% improvement in fuel economy over throttle body fuel injection.
Overhead Camshaft (OHC)	At equal power, OHC engines achieve 1.5, 2.0, and 3.5% better fuel economy than overhead valve engines as reported by GM, Ford, and Chrysler.[37] Advantages of OHC are the following: • Inertial forces in the valve train are reduced • Friction is reduced because of fewer moving parts • Valve opening time can be reduced, which improves low speed torque and fuel economy • Increased flexibility in valve location and thus improved shape of the combustion chamber
Four Valves per Cylinder	Four-valve (two for intake and two for exhaust) engines have a higher fuel economy compared to two-valve engines for the following reasons: • Pumping loss is reduced because of less aerodynamic resistance • Spark plug can be positioned closer to the center of the combustion chamber, which decreases flame propagation distance, improves mixing, and results in higher combustion efficiency[56] • Results in retarded ignition timing, thus decreasing the dwell time for the hot gases in the combustion chamber and reduces the formation of NO_x However, the applicability of four-valve engines will be limited by their low torque at low engine speeds.[37]
Variable Valve Timing and Lift Control	Variable valve timing and lift control optimizes the opening and closing of intake and exhaust valves for best fuel economy. Under lean burn conditions, such technology can generate a swirling vortex motion of rich fuel-air mixture near the spark plug, resulting in smooth operation at low rpm. Honda's VTEC-E engine uses a combination of four valves per cylinder and variable valve and lift control to generate high torque at low speeds.[37]
Lean-Burn Engine	Lean-burn engines operate at an air-fuel ratio higher than stoichiometric (i.e., greater than 15:1 for gasoline fuel). Advantages of lean burning include reduced pumping loss, improved thermal efficiency, and potentially reduced CO emission. The HC emissions may or may not increase, depending on engine requirements. A disadvantage is the difficulty of catalytic NO_x reduction under lean conditions.[38]
Boosting	Boosting (supercharging and turbocharging) forces high-pressure air through the intake manifold into the combustion chamber, thus increasing volumetric efficiency and increasing fuel economy. However, maximum boosting is limited by the onset of knock caused by high engine temperature.[57]

Drivetrain Performance

The drivetrain links the engine to the wheels. The PNGV reported 5.6% and 5.4% of fuel energy loss in urban and highway driving, respectively.[46] Drivetrain components include the transmission, clutch, torque converter, drive shaft, universal joints, differential, final drive assembly, and axle shafts. An automotive drivetrain varies the ratio of engine speed to vehicle speed, thus allowing more optimal engine operation and a wider range of speeds than would be feasible if the engine were connected directly to the drive wheels.[37] The drivetrain delivers different torque and power to the wheels, depending on the engine load. The transmission and final drive assembly are the two most important drivetrain components in terms of fuel consumption. The drivetrain affects fuel economy in two ways:

- Energy is lost in friction within the transmission
- The range of gears and their shift points allow the engine to operate at its most fuel-efficient operating regime over a wide range of operating speeds and loads without sacrificing performance

Some measures to reduce drivetrain losses are transmission improvement, low N/V ratio, and improved design of the hypoid gear for the universal joint.[37,57] The N/V ratio corresponds to the number of engine revolutions per distance traveled in top gear. Fewer engine revolutions per mile means less energy lost to engine friction. Examples of transmission improvements are adding gears to the existing gear system, torque converter lockup, continuously variable transmission (CVT), and optimized transmission control. A CVT allows an engine to operate at the lowest possible rpm under a given load and increases the rpm when more power is needed. Optimized transmission control is implemented electronically by synchronizing the transmission with the engine under given engine operating conditions. Optimized transmission is a strategy for facilitating low rpm, open throttle operation at low and moderate loads, while providing downshifts to access greater power when needed.

Rolling Resistance

Rolling resistance arises primarily from the periodic flexing of tires as they bear the weight of the vehicle and provide driving, braking, and cornering forces while rotating. The PNGV reported that rolling resistance accounts for 4.2% of fuel energy used during urban driving and 7.1% of fuel energy used during highway driving.[46] Rolling resistance contributes 33 to 35% of the shaft energy in urban and highway driving. Another study[58] indicated that rolling resistance accounts for 6% of total fuel energy and 30% of energy available at the wheel. Two independent surveys[53,55] concluded that tire rolling resistance can be reduced by approximately 10% during the next decade. To reduce automobile fuel consumption by 1%, tire rolling resistance must be reduced 6 to7%.[55,58]

The essential construction feature of a modern pneumatic tire is the carcass—a molding of rubber reinforced by several layers of cords or fabric. Each layer is called a ply.[59] The carcass makes contact with the wheel at the bead. The bead is the interference fit on the rim, which has a taper of approximately 5°. Pressures typically are 120 to 200 kPa for cars. The reinforcing cords—typically nylon, rayon, or terylene—have a higher modulus of elasticity than rubber and less creep. Therefore, they carry the tension while rubber acts essentially as a gas sealant. Tire tread is patterned with grooves, slots, and sipes to a depth of 8 mm to encourage drainage in wet conditions and to assist cooling in dry conditions. The aspect ratio of tires is the ratio of section height to section width and can have values of 50 to 82%. For racing cars, the aspect ratio can be as low as 30%. Tire design is a function of wheel diameter, section width, and load-carrying capacity.

Tire rubber consists of natural and synthetic rubber and other constituents such as carbon black and oil. Average density is approximately 1200 kg/m^3. A complete tire consists of several different blends of rubber, each optimized for properties and cost according to specific application (e.g., tread, carcass wall, bead filler, or inner liner). Each modern passenger-car tire has a mass of approximately 12 kg, comprising approximately 4 kg of rubber, 2 kg of carbon black, 2 kg of oil extenders, 3 kg of steel, and 1 kg of rayon.[59]

Rolling resistance is defined as

$$F_R = \mu_R F_V$$

where F_V is the vertical force and μ_R is the rolling resistance coefficient, which varies from 0.01 to 0.025 for cars. Usually, the total rolling resistance of a good tire is apportioned as 90% material hysteresis, 8% surface friction, and 2% air friction at moderate speed.

Rolling resistance decreases as inflation pressure increases. Changes in the rolling resistance coefficient with load are small.[60] To minimize rolling resistance, a tire should operate at high inflation pressure and relatively high working temperature, contain natural rubber, and have a low aspect ratio, minimum tread depth, and zero slip angle.[58]

Road characteristics that can affect rolling resistance include whether the surface is paved, cobbled, or unpaved; surface texture; roughness or unevenness; softness or depth of loose material if the road is unpaved; gradients; and the material from which the road is constructed. Rolling resistance coefficients of different surfaces are indicated below[61]:

Large Sett Pavement	0.015
Small Sett Pavement	0.015
Concrete, Asphalt	0.013
Rolled Gravel	0.020
Tarmacadam	0.025
Field	0.050

Energy and Environmental Analysis, Inc., estimates the rolling resistance of average, new-car tires at 0.011 in recent years and projects a decrease to 0.0085 by the year 2001.[55] A recent review[57] suggests possible near-term, new-fleet-average rolling resistance coefficients of 0.0085, 0.0075, and 0.0065 at certainty levels of one to three, implying fuel economy benefits in miles per gallon of 3.4%, 4.8%, and 6.1%, respectively.

For a given vehicle mass, rolling resistance reduction can result from both reduction of tire weight and rolling resistance. Tire mass, including crown reinforcement materials, can be reduced from the current average of approximately 10 to 12 kg per tire to an estimated 4.5 kg.[62] Rolling resistances of some modern tires are listed below.[62]

Michelin XSE Tire	0.008
Aero Radials Tested by GM	0.0048
Goodyear Tire	0.007

A potential area of concern for low-rolling-resistance tires is the loss of traction under adverse driving conditions (i.e., rain, mud, or snow).

Aerodynamics

Aerodynamic drag is a force opposing vehicle motion. The resistance of ambient air to vehicle motion produces forces and moments that depend on aerodynamic pitch, yaw, and roll. Vehicle motion causes a stagnation point in the front and a flow separation region of concentrated vortex at the rear. Flow occurs over and beneath the vehicle, causing lift and drag.

The drag coefficient of a typical vehicle decreased from 0.8 to below 0.25 from 1920 to 1990.[59] Various studies suggest that aerodynamic drag typically is distributed as follows: 65% form drag, 15% interference drag, 5% internal (engine and cabin cooling) drag, 5% skin drag, and 10% lift-associated drag; however, this will vary substantially among vehicles. Table 5.15 indicates the frontal area and various aerodynamic coefficients for a modern automobile.[59] Moore and Lovins[62] estimated a frontal area of 1.95 m^2 as a baseline for a six-seater PNGV design.

Drag force varies as a square of the velocity as shown by:

$$F = \frac{1}{2} C_D A_{\rho} V^2$$

TABLE 5.15. AERODYNAMIC COEFFICIENT FOR CURRENT PRODUCTION VEHICLE

Parameters	Metrics
Frontal Area	2.30
Drag Area	1.05
Vertical Lift	0.30
Drag	0.35
Pitch	-0.05
Side Lift	0.040/deg
Yaw	0.005/deg
Roll	0.005/deg
Height Dependence of Lift Coefficient	-0.2/m
Angular Dependence of Lift Coefficient	0.06/deg
Height Dependence of Drag Coefficient	0.5/m
Angular Dependence of Drag Coefficient	0.015/deg
Angular Dependence of Pitch	0.03/deg

Source: Ref. 59.

Thus, the power to overcome drag force varies as the cube of the velocity. Drag increases parabolically with speed and exceeds rolling resistance at approximately 30 mph (50 kph). For a typical compact vehicle, drag is 0.71 MJ.[63] At a typical wind speed of 10 mph in the Detroit area, the drag coefficient increases by 20% at a vehicle velocity of 30 mph, 45% at a vehicle velocity of 20 mph, and more than 70% at a vehicle velocity of 14 mph.[63]

Typical considerations for low-drag design include the following:

- All forward facing corners should be rounded
- Vehicle front should have some taper toward the front
- Low bonnet front and raked wind screens
- The hood should be sloping
- Vehicle rear sides should be boat tailed
- Optimized spoiler mounted at the rear
- Roof should be curved down at the back end
- Underbody should be smooth

The average new-car drag coefficient (C_D) in 1990 was 0.352 (±0.037), with 25% of models having a C_D of 0.33 or less.[57] The GM Opel Calibra has a C_D value of 0.26. Energy and Environmental Analysis, Inc., suggests that a new fleet C_D average of approximately 0.23 is attainable by the year 2010.[55] A recent review[57] suggests that near-term, new-fleet average C_D values of 0.28, 0.27, and 0.26 at certainty levels of one to three are possible, implying a fuel economy advantage in miles per gallon of 3.3%, 3.8%, and 4.3%, respectively. Over the EPA Federal Test Procedure (FTP), fuel economy varies with C_D with an average elasticity of 0.2. That is, a 10% reduction in C_D will produce a 2.3 to 2.4% increase in miles per gallon.[53,64] Table 5.16 shows that a significant demonstrated potential exists to reduce the drag coefficient of automobiles.

Braking

The braking energy required to stop a vehicle in motion is equivalent to its kinetic energy. Thus

$$E_B = \frac{1}{2} M V^2$$

where M is the mass of the vehicle and V is the velocity.

Braking results in 5.8% of fuel energy loss in urban driving and 2.2% of fuel energy loss in highway driving. Regenerative braking can reclaim energy that otherwise would be lost. A motor and an advanced energy storage device are needed to capture and resupply the energy. Such energy storage and retrieval system can be flywheels, advanced batteries, or ultracapacitors.[46]

Accessories Performance

Accessories either perform essential engine-supporting functions (e.g., water pump, oil pump, cooling fan, and alternator) or provide optional services for the driver and occupants (power steering pump and air conditioning compressor). The PNGV estimates that accessories in a conventional vehicle use about 2.2% of fuel energy in urban driving and 1.55% of energy in highway driving.[46] Power steering alone reduces fuel economy by approximately 1 mpg.[66] Another study puts this affect at approximately 15%.[55] Accessories typically require the same amount of energy regardless of vehicle size; therefore, they have a somewhat greater proportional impact on the fuel economy of small cars. Fuel economy can be improved by increasing the efficiency of accessory systems or by improved matching of their operation to requirements.

A significant amount of improvement has already occurred. Several surveys[53,55] estimate that accessories operated by variable speed drives can result in a 0.5 to 1% efficiency improvement over comparable single-speed drives at the expense of higher cost.

The EPA recently demonstrated the impacts of air conditioning (A/C) on fuel economy in a simulation of hot, sunny, mid-afternoon conditions (95°F ambient temperature, 40% relative humidity, and 135°F road surface temperature) using CF-134a refrigerant in the A/C. Under these conditions, EPA observed increases in average emissions of 25% for HC (0.09 to 0.11 g/mi), 51% for CO (1.0 to 1.5 g/mi), and 92% for NO_x (0.21 to 0.41 g/mi) over the full FTP.[20]

Driving with open windows as an alternative to air conditioning also lowers fuel economy. The EPA studied fuel economy effects of both air conditioning and open windows in 1980. Data reported in this study of automobiles that are now virtually all retired are shown in Figure 5.7. For these

TABLE 5.16. DRAG COEFFICIENT FOR CURRENT AND FUTURE VEHICLES

Vehicle Model	C_D	Source
Current Production		
Average New Car, 1990	0.35	Ref. 57
Average New Car, 1990	0.33	Ref. 65
GM Opel Calibra	0.26	Ref. 65
Future Car (projected based on current fleet)	0.23	Ref. 55
Demonstrated Concept Car		
GM Ultralite, 1991	0.19	Ref. 65
ESORO H 301, 1994	0.19–0.22	Ref. 65
Hypothetical Hybrid Ultralight		
Conservativa	0.21	Ref. 65
Gaia	0.14	Ref. 65
Ultima	0.10	Ref. 65
Imagina	0.09	Ref. 65

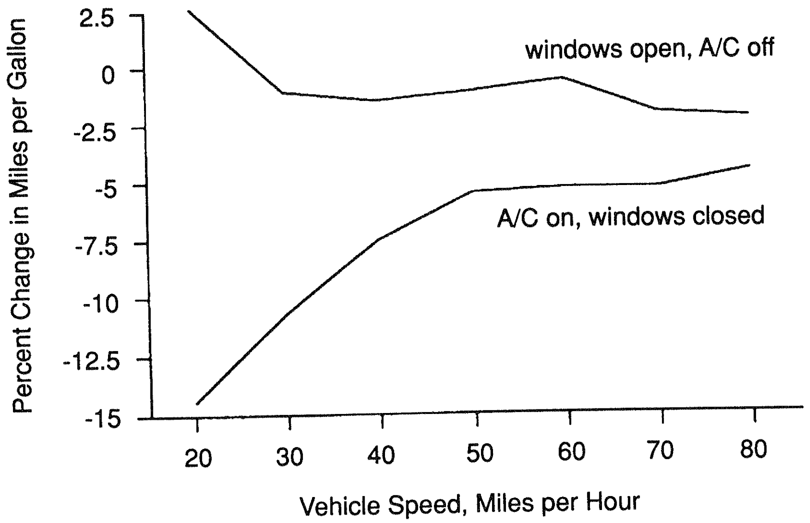


Fig. 5.7 Open windows vs. A/C fuel economy effects in 1980-era automobiles. (Source: Ref. 67.)

automobiles, air conditioning was more detrimental to fuel economy than open windows. Whether this relationship continues to hold for modern, aerodynamic designs should be studied. Vehicles also may be better optimized for windows-down operation, although consumer behavior may be difficult to change.

Mass Reduction

In 1976 the average curb weight of all domestic and foreign new automobiles sold in the United States was 3600 lbs. This sales-weighted, new-car average declined to 2675 lbs (26%) by 1986 before rising again to 2885 lbs by 1992. Most of the initial weight reduction was achieved from 1976 to1980 by downsizing. Subsequent weight reduction was due in large part to the use of a wide array of lightweight materials in the vehicle. Although this trend continues, average weights increased by almost 8% between 1986 and 1992. Weight reduction and recyclability issues will become even more significant as the automotive industry begins to target goals of PNGV.

Lightweight materials are one of the primary research areas for PNGV. Mass is a key factor in improving fuel economy because rolling resistance and acceleration force are directly proportional to mass. Mass not only influences vehicle energy use and tailpipe emissions during operation; it also directly affects energy use and pollutant emissions during material production, manufacturing, and end-of-life management. Therefore, mass is the single most important factor in improved fuel economy. A 1% mass reduction yields a 0.66% fuel economy improvement if engine displacement is reduced to hold acceleration ability constant.[55] DeCicco, John, and Ross[57] project that mass can potentially be reduced 10 to 30% by the year 2000.

Mass is the single largest contributor to both intermittent and continuous peak power requirements. Adding 10% to mass raises the power required to maintain 60 mph on a 6% grade by approximately 5% and the power required for 0–60 mph acceleration in less than nine seconds by approximately 7%.[68]

Mass decompounding is nonlinear and discontinuous, stemming from the need for a lighter engine to have a lighter body to carry it. A typical mass decompounding factor of 1.5 is used for the production cars, although it may vary from 1.3 to 1.75.[62] This means that if 100 kg are saved by material substitution, then 50 kg more can be saved by downsizing components and structure. Mass decompounding requires a systems approach to reduce unnecessary vehicle components.

The use of lightweight materials for the body in white (BIW) largely decouples the vehicle mass from size, allowing substantial mass reductions without downsizing. Mass reduction possibilities for three materials are as follow[62]:

Steel	The American Iron and Steel Institute (AISI) claims that vehicle curb-mass reductions up to 40% can be achieved with a "holistic" approach to design.[69] This considers the mass decompounding effect. Porsche Engineering Services calculated the realistic, achievable potential for BIW mass reduction to be 15–20%, with a theoretical maximum of 30%.[70]
Aluminum	Ford's 199-kg Taurus/Sable AIV (aluminum-intensive car) BIW has demonstrated a 47% mass reduction for a midsized vehicle.[71] This was accomplished without considering mass decompounding. A recent analysis[72] suggests that by using aluminum, BIW mass reductions up to 55% may be technically feasible for high-volume, production automobiles by the year 2000, although the economics of doing so remain uncertain.
Composites	These materials offer significantly reduced mass while maintaining high strength, stiffness, and fatigue resistance. Current industry analysis indicates that the potential BIW mass reduction using carbon-fiber-reinforced composites is 60 to 70%.[73] The BIW for a full-sized, carbon-fiber-composite Ford LTD built in 1979 weighed 51% less than its production counterpart.[71] However, this design was not optimized, being based on standard panel design rather than a redesigned monocoque. The BIW with closures, GM Ultralite, weighs 191 kg; ESORO's H301 hybrid was 150 kg. Without closures, the Ultralite weighs 140 kg, compared to the ESORO which weighs about 72 kg.[74] The BIW for a 1995 Ford Taurus is 372 kg with closure.

Reducing vehicle weight represents an important strategy for improving fuel economy. Substitution of lightweight materials can offer an important means of improving fuel economy by reducing rolling resistance and braking energy. Heavier vehicles require more energy for accelerating and maintaining speed and dissipate more braking energy for stopping. Examples of lightweight materials are high-strength steel, aluminum, magnesium, titanium, intermetallics, metal matrix composites, polymeric composites, nonreinforced polymers, and reinforced polymers. Cost often limits the application of lightweight materials. In the case of polymeric materials, recycling also presents a major challenge.

Potential areas for research and development in lightweight materials may include the following[46]:

- Low-cost sheet aluminum
- Damage-resistant aluminum components for primary structure and body panels
- Low-cost aluminum, magnesium, and titanium casting technology
- Glass- and carbon-fiber composites for primary structure and body panels (with emphasis on cost and recyclability)
- Joining technology for lightweight metal and composites, including adhesives
- Advanced ceramics for engine weight reduction, friction reduction, and improved thermal performance
- Glazing materials as substitutes for glass

The fuel economy benefits from different technologies are presented in Table 5.17. Results are developed for the following three levels of technical certainty[57]:

Level 1 Technologies	Already in production in at least one worldwide mass market; face no technical risk because they are fully demonstrated and available
Level 2 Technologies	Ready for commercialization and face no engineering constraints (such as emission control considerations) that inhibit their use in production vehicles, but entail some risk because of limited production experience
Level 3 Technologies	In advanced stages of development, but face some technical constraints before they can be used in production vehicles

Information in Table 5.17 is used to evaluate fuel energy losses for the different levels of technology shown in Table 5.18. Improved technology will result in less fuel energy loss in level i vehicles compared to current production vehicles. The difference is equal to the percent gain in fuel economy in miles per gallon multiplied by available road load for current production vehicles (i.e., 12.6% fuel energy).

Thus, fuel energy loss for level i vehicles can be calculated as:

$$E_{Li} = E_c - f \times L$$

TABLE 5.17. FUEL ECONOMY BENEFIT ESTIMATE

Components		Technology	Fuel Economy Benefit (%) Level 1	Level 2	Level 3
Engine					
	Thermodynamics	Multipoint fuel injection	3.0	3.0	3.0
		Four valves per cylinder	6.6	6.6	6.6
		Overhead camshaft	3.0	3.0	3.0
		Compression ratio increase	1.0	1.0	1.0
		Variable valve control	12.0	12.0	12.0
		Supercharging	5.0	5.0	8.0
		Variable displacement	0	5.0	5.0
		Idle off	0	6.0	6.0
		Lean burning	0	0	10.0
		Total	**30.6**	**41.6**	**54.6**
	Friction	Friction reduction	**6.0**	**6.0**	**6.0**
Accessories		Accessory improvement	**1.7**	**1.7**	**1.7**
Drivetrain		Five-speed automatic transmission	5.0	5.0	5.0
		Continuously variable transmission	6.0	6.0	6.0
		Torque converter lockup	3.0	3.0	3.0
		Optimized transmission control	0.5	9.0	9.0
		Total	**14.5**	**23.0**	**23.0**
Drive shaft		Lower-rolling-resistance tires	3.4	4.8	6.1
		Aerodynamic improvement	3.3	3.8	4.3
		Weight reduction	3.9	9.9	15.9
		Lubricant improvement	0.5	0.5	0.5
		Total	**11.1**	**19.0**	**26.8**
		Total All Technology	**63.9**	**91.3**	**112.1**

Source: Ref. 57.

TABLE 5.18. FUEL ENERGY LOSS FROM DIFFERENT AUTOMOTIVE COMPONENTS

Components	Energy Loss Mechanism	Fuel Energy (%) Current	Level 1	Level 2	Level 3
Engine	Thermodynamics	62.4	58.5	57.2	55.5
	Mechanical and fluid friction	17.2	16.4	16.4	16.4
Accessories	Load	2.2	2.0	2.0	2.0
Drivetrain	Mechanical and fluid friction	5.6	3.8	2.7	2.7
Drive shaft	Road load, F1	12.6	11.2	10.2	9.2
	- Rolling friction				
	- Aerodynamics				
	- Braking				

where

E_c = Fuel energy loss in different components of the current production vehicle

E_{Li} = Fuel energy loss in different components of level i concept vehicle (i=1, 2, 3)

f = Percent gain in fuel economy in miles per gallon relative to the current vehicle

L = Road load of the current production vehicle

In Table 5.19, fuel economy for level i vehicles is calculated using fuel energy from Table 5.18. For current vehicles, road load is equal to the power available in the drive shaft. Level i technology offers reduction in engine and drivetrain energy loss, rolling resistance, and aerodynamic drag. Thus, more power is available in the engine driveshaft than the necessary road load. This leads to a significant improvement in fuel economy.

5.3.2 Emissions

This subsection on vehicle emissions is classified into three categories: emissions control technology, emissions measurement technology, and emissions trends.

Emissions Control Technology

Exhaust emissions, fuel economy, and power are functions of the fuel-air ratio within the engine. The fuel-air ratio dictates the combustion process and the by-products of combustion (i.e., the exhaust gas composition).[61] Approximately 14.5 kg of air are required for complete combustion of 1 kg of gasoline. The amount of air available for fuel combustion is generally expressed in terms of the excess-air factor as:

$$\lambda = \frac{\text{quantity of intake air}}{\text{theoretical air requirement}}$$

where

$\lambda = 0.5$: rich limit for engine operation

$\lambda < 0.9$: for overrun (trailing-throttle) operation

$\lambda = 0.9$: maximum torque and smoothest operation

$\lambda = 1.1$: optimum fuel economy is achieved, setting of low CO and HC emissions, maximum NO_x

$\lambda = 0.9$–1.05 : idle condition

$\lambda > 1.1$: engine lean misfire limit (LML) being reached or exceeded, misfiring causes rapid increase in HC emission

$\lambda = 1.3$: lean limit for engine operation

Figure 5.8 illustrates that for a given vehicle, conditions for high fuel economy (low fuel consumption), low HC and CO emissions, and moderate power are associated with high NO_x emissions. This relationship suggests that different technologies are required to control HC, CO, and NO_x emissions.

Table 5.20 illustrates factors causing exhaust gas emissions and strategies for controlling them.

Although CO_2 is the major constituent of exhaust gas, CO_2 control is not discussed because CO_2 emissions are proportional to fuel energy used during combustion. From Table 5.19, it can be interpreted that engines with effective crevice design, spark retard, EGR control, slightly lean operation, and catalytic control would result in low HC, CO, and NO_x emissions.

Emissions control technology can be grouped into two categories[61]:

- Engine design measures
- Exhaust gas treatment

The selection of procedures to be employed in any given country is determined by its specific legal requirements.

TABLE 5.19. ENERGY AVAILABLE IN CURRENT AND FUTURE VEHICLES

	Current Vehicle	Level 1	Level 2	Level 3
Mass, M (kg)	1400	1260	1120	980
Fuel Economy (mpg)	27.0	44.2	51.6	57.3
Energy Type		Energy Available, % of Total		
IHP	37.6	41.5	42.8	44.5
BHP	20.4	25.1	26.4	28.1
Shaft Power, F2	12.6	19.3	21.7	23.4

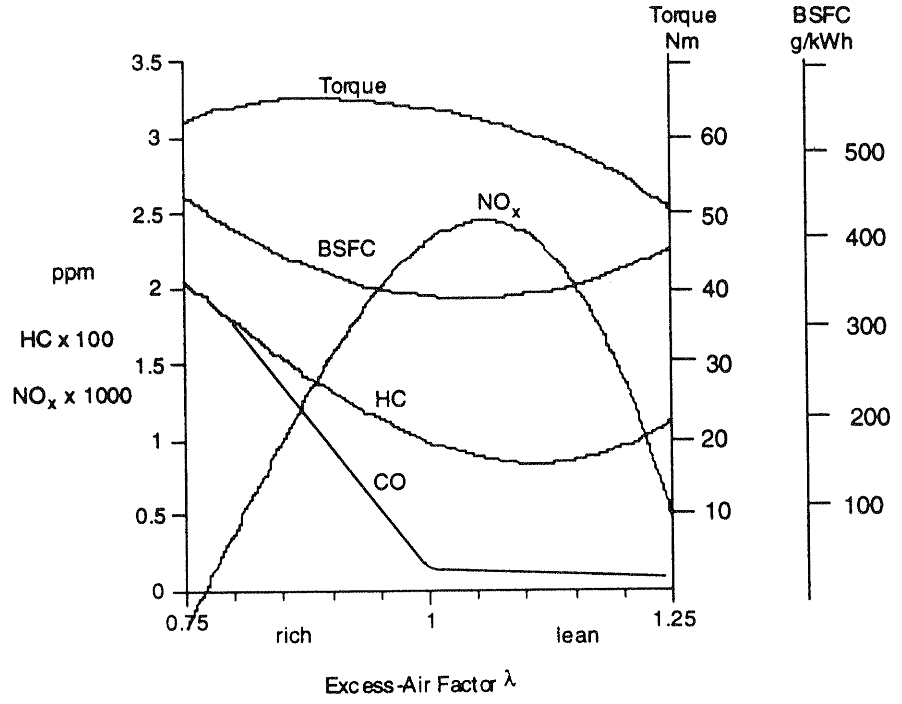


Fig. 5.8 Effect of fuel-air ratio on emissions, fuel economy, and power. (Source: Ref. 61.)

ENGINE DESIGN MEASURES

Fuel Metering	Currently, all engines are operated at stoichiometric fuel-air ratio l = 1. This allows the three-way catalytic converter to treat raw emissions with maximum effectiveness, thereby facilitating compliance with legal emission limits. However, under certain operating conditions, such as starting, warm-up, and acceleration, the mixture must continue to be enriched to obtain good starts, smooth operation, and brisk engine response. Multipoint fuel injection is used for precise mixture control and can result in low emissions.
Mixture Formation	Mixture formation influences the fuel-air ratio and the mixture homogeneity, with consequent effects upon exhaust-gas composition. Some of the development options are: • Homogeneous mixture and controlled stratification— rich mixture at the spark plug, lean mixture in the vicinity of the combustion chamber walls • Preheated intake air and intake manifold—inhibits formation of fuel film on the manifold walls
Uniform Distribution	An efficient fuel-air distribution system ensures that every cylinder is operated with the same excess-air factor, thus resulting in maximum engine efficiency.
Exhaust Gas Recirculation (EGR)	EGR is an effective means to reduce peak combustion temperatures and hence control the formation of NO_x. EGR can be implemented in either of two ways: • Internal exhaust gas recirculation is achieved with appropriate valve timing (overlap) • External exhaust gas recirculation employing controlled EGR valves
Valve Timing	Internal exhaust gas recirculation can be implemented using large valve overlaps, but at the cost of rough idling and increased HC emissions. Thus, variable valve timing is desirable as a means of reducing emissions.
Compression Ratio	From thermodynamics, increases in compression ratio result in increased thermal efficiency and a consequent decrease in emissions. However, engine design factors such as crevice volume are affected by compression ratio, resulting in a decrease in HC emissions with CR. High compression ratio also results in higher peak temperature, thus causing higher NO_x emissions.
Combustion Chamber Design	Low HC emissions are achieved with a compact combustion chamber featuring a minimal surface area and no recesses. A centrally located spark plug with short flame travel produces rapid and relatively complete combustion of the mixture, resulting in low HC emissions and reduced fuel consumption. Induced turbulence in the combustion chamber also provides rapid combustion while making it possible to employ leaner mixtures. External measures such as controlled vortex in the intake tract also can result in optimized combustion in lean-burn engines.
Ignition System	Spark plug design, its position within the combustion chamber, and spark energy and duration influence the ignition and combustion process, with attendant effects on emission levels. Reduction of NO_x and unburned HC can be achieved by adjusting the spark timing such that the exhaust valve opens before the combustion process is completed, inducing a thermal reaction in the exhaust system. Although this method achieves reduction in NO_x and unburned HC, it also results in higher fuel consumption.

TABLE 5.20. FACTORS CAUSING EXHAUST EMISSIONS AND STRATEGIES FOR CONTROL

Exhaust Gas	Effects of Process Variable	Relevant Vehicle System for Improvement
HC	• HC is product of incomplete combustion • Engine-out HC emissions during stabilized running and cold start represent approximately 85% of the total emissions; the last portion of exhaust gas contains high HC emissions • Sources of HC: - Unevaporated fuel droplets trapped in ring area, wall quenching of flame - HC burnup in port • HC emissions increase with compression ratio (CR) because of increase in crevice volume • Spark retard and effective crevice design decrease HC emissions but reduce fuel economy • Increasing exhaust back pressure reduces HC emissions but lowers fuel economy and power • HC increases with EGR	• Ring area design, elimination of crevice volumes, blowby, direct cylinder injection • Port design • EGR strategy • Fuel availability, exhaust system design • Engine design • Fuel metering system
	• NO_x is a high-temperature (approximately 2800 K) phenomenon, activation energy = 130 Kcal/mole • Stabilized running and high-power operations cause approximately 75% of total NO_x emissions • NO_x decreases with EGR, but burn rate can be a problem, and EGR and fresh charge temperature must be fairly uniform • Spark retard reduces NO_x and fuel economy • First element of charge to burn produces most of NO_x • Increasing CR will increase NO_x • Stratified charge (first element fuel-rich and last element fuel-lean) can decrease NO_x	• Increased turbulence, dual ignition • Intake air preheating • Fuel injection
CO	• Product of incomplete combustion • For CO emissions, contributions from high-powered operations, stabilized running, and cold/hot start each represent approximately 30–37% of the total FTP emissions • Requirements for low CO emissions and high fuel economy coincide—lean operation • Diesel engine runs lean in all modes and does not have large cold-start CO emissions	• Fuel metering system

Source: Refs. 21, 49, 50, 75, and 76.

Crankcase Ventilation	Crankcase emission control is a standard legal requirement. It involves intake of crankcase gases into the combustion chamber for burning rather than allowing them to escape to the atmosphere.

EXHAUST GAS AFTERTREATMENT

Thermal Afterburning	Thermal afterburning employs a specific residence time at high temperatures for burning the exhaust gas components that failed to combust during normal combustion in the engine cylinders.[61] In the rich fuel-air mixture range ($\lambda < 1.0$), the process must be supplied with supplementary air injection. In the lean range ($\lambda > 1.0$), the residual oxygen in the exhaust gas is sufficient for afterburning. Thermal afterburning is not currently used in automobiles because it does not lower NO_x emissions. However, it can be employed to reduce HC and CO emissions in the warm-up phase before the catalytic converter reaches operating temperature. The catalytic converter is composed of a carrier substrate, which serves as a base for the catalytic material, mounted within a housing using vibration-proof, heat-insulated supports.[61] Granulate and ceramic or metallic monolith structures are employed as substrate materials. Monolith structures have the following advantages: maximum utilization of catalytic surface, durability combined with physical strength, low thermal retention, and limited exhaust back pressure. The active catalytic layer consists of small quantities of noble metals (Pt, Rh, and Pd) and is sensitive to lead. The conversion rate of the catalytic converter is largely a function of operating temperature; no meaningful treatment of pollutants occurs until the converter has reached an operating temperature of approximately 250°C. Operating temperature of approximately 400 to 800°C provides ideal conditions for maximum efficiency and extended service life. The position of the catalytic converter relative to the engine is critical, because a converter mounted too close to the engine would be subject to thermal stresses. On the other hand, it would result in optimum efficiency because of high temperature in the catalytic converter. Catalytic converters can be of different types:
Catalytic Afterburning *(continued)*	• Oxidation catalytic converter: oxidizes CO and HC either by using excess air supplied by lean engine mixtures or by relying on secondary air injection • Reduction catalytic converter: operates with air deficiency to reduce NO_x levels • Dual-bed catalytic converter: combines the reduction and oxidation catalytic converter in series and thus can result in control of NO_x, HC, and CO levels when supported with secondary air injection; disadvantages include design complication and required engine operation in the high-fuel-consumption range • Three-way catalytic converter: with lambda, closed-loop control has proven to be an effective means of reducing HC, CO, and NO_x emissions, provided the engine is operated with a stoichiometric mixture; in this closed-loop system, an exhaust gas oxygen sensor (EGOS) called a lambda sensor continuously monitors exhaust gases to provide information required for instantaneous adjustments to the fuel metering system.

Alternative engines potentially have better fuel consumption and lower emissions than conventional engines, as indicated in Table 5.21.

Emissions Testing

Vehicle emissions are determined as part of the certification procedure. The vehicle is tested in an emission test cell under standardized conditions which are intended to accurately reflect actual driving conditions.[61] The vehicle to be tested is parked with the drive wheels on special rollers having a rotating resistance that can be adjusted to simulate friction losses and aerodynamic resistance, while inertial mass can be added to simulate the vehicle's weight. The required cooling is provided by a fan mounted a short distance from the vehicle.

Fluid friction dynamometers, eddy current brakes, and DC motors simulate the inertial forces that rolling and aerodynamic resistance exert on the vehicle by providing a corresponding, velocity-dependent braking force. Rapid couplings in various sizes are used to connect inertial masses to the rollers, thus simulating vehicle weight. The progression curve for braking loads must correspond to that for vehicle speeds, and the required inertial masses must be maintained precisely. Ambient conditions such as atmospheric humidity, temperature, and barometric pressure also influence test results.

TABLE 5.21. FUEL ECONOMY AND EMISSIONS FOR VARIOUS ENGINES

Engine/Status	Fuel Consumption l/100 km	Fuel Consumption mpg	Emissions NO_x (g/km)	Emissions CO (g/km)
Spark Ignition Engine				
Production[a]	8	29.4	0.23	0.76
Diesel Engine				
Production	6.2	38.0	0.72	0.99
Gas Turbine Engine				
Prototype	8.3	28.3	0.07	0.27
Potential			0.04	0.07
Stirling Engine				
Prototype	8.6	27.3	0.12	0.04
Potential			0.02	0.02
Steam Engine				
Potential	5.4	43.5	0.04–0.06	0.12–0.18
Alternative			0.10–0.02	0.01–0.02

a Typical value for current vehicles.
Source: Ref. 77.

Emission levels are measured based on a simulated driving pattern which progresses through a precise driving cycle incorporating various vehicle speeds. The exhaust gases produced during this procedure are collected for subsequent analysis of pollutant mass.

Federal Test Procedure

The EPA Federal Test Procedure (FTP) is the test procedure used in the United States to determine compliance of light-duty vehicles (LDV) and light-duty trucks (LDT) with federal emission standards as part of 40 CFR 86, Subparts A and B.[42] The FTP is used to test preproduction vehicles for motor vehicle certification and production, and in-use vehicles for compliance with appropriate emission standards. The principal elements of the test are designed to test evaporative and exhaust emissions under several simulated situations.

Evaporative emission tests include the following:

- Diurnal test: Fuel tank is heated to simulate heating by sunlight, and emissions are measured
- Hot-soak test: Emissions are measured after the car has been driven and parked with a hot engine

Exhaust emissions are measured by driving the vehicle on a dynamometer under simulated urban driving with two conditions:

- Cold start: Designed to represent a morning start-up after a long soak (a period of non-use)
- Hot start: Occurs while the engine is hot

The FTP also encompasses all factors relevant to vehicle testing such as fuel, vehicle preconditioning, ambient temperature and humidity, aerodynamic loss, and vehicle inertia simulations. In addition to evaporative and exhaust emissions, the FTP is used in evaluating fuel economy.

The FTP test cycle is designed to represent speeds measured on the streets of Los Angeles in morning commuter traffic. The following assumptions are made:

Distance	Cycle distance: 11.115 miles Average distance between stops: 0.41 miles
Duration	Cycle duration: 1877 s + 600 s pause Soak period: 10 min and 12–36 hrs Cold phase (ct): 0–505 s Stabilized phase: 505–1372 s

Duration *(continued)*	10 min break (engine off) Hot phase: 1972–2477 s Idle time after cold and hot start: 20 s
Temperature	Ambient temperature: 20–30°C, -6.7°C. Start-up: 57% of all starts occur with hot catalysts, 43% of all starts occur with cold engines
Speed	Average speed: 19.6 mph Maximum speed: 56.7 mph Average speed in the first 80 seconds: 23.1 mph Average in-use speed 81–240 seconds: 29.8 mph
Acceleration	Maximum acceleration rate: 15 mph/s, standard deviation 1.5
Power	Maximum power: 192 mph/s Average power: 38.6 mph/s Median power: 21.6 mph/s

MOBILE 5.0 Emission Factor Model

MOBILE 5.0 is the most commonly used inventory model for estimating on-road vehicle performance.[20,78] This model is continuously refined based on test data and research performed at EPA. Typical factors considered in the MOBILE emission model are listed below. The average emission rate from a vehicle depends on several factors[78]:

- Age distribution of in-use vehicle fleet
- VMT per year of a certain vehicle age
- Emission from a car of a given age
- Rate of deterioration of emissions control
- Effect of tampering
- Reduction in emissions resulting from inspection and maintenance program
- Ambient temperature
- Average driving speed
- Driving pattern

To varying degrees of detail, these factors and the FTP test results are used to construct the mobile emissions inventory model.

The source inventory data are fed into computer models of atmospheric dispersion and ozone formation chemistry to varying degrees of sophistication to form predictions of ambient concentrations.[78] These predictions are usually calibrated with a specific air pollution episode in the urban area of interest for which data on the concentrations of ambient pollutants are available.

During the last five years, vehicle emissions have been measured in the air flowing out of the Van Nuys Tunnel in California, the Fort McHenry Tunnel in Baltimore, and the Tuscarora Mountain Tunnel in Pennsylvania.[20] These studies measured concentrations of CO and HC approximately twice that predicted by MOBILE 5.0. The studies have raised questions about the size of emissions of mobile sources, factors used to characterize the influence of external patterns on vehicle emissions, and the uncertainty in estimating stationary, biogenic, and natural emissions.

5.3.3 Alternative Fuels for Internal Combustion Engines

The Energy Policy Act of 1992 included alternative fuel mandates. In 1993 the federal government established requirements to procure alternative fuels. Interest in alternative fuels comes primarily from the limited petroleum reserves. Petroleum accounted for 38% of total world energy consumption in 1988; at this rate, petroleum reserves are expected to last 50 to 60 years.[79,80] The U.S. transportation sector produces approximately 425 million metric tons of CO_2 from gasoline combustion annually.[7]

In response to oil crises of the 1970s and 1980s, several alternative fuels were developed. Currently, alternative fuel development occurs mainly in response to environmental concerns. Some typical alternative fuels are compressed natural gas (CNG), liquefied petroleum gas (LPG), methanol, ethanol, and hydrogen. In addition, the viability of a zero-emission electric vehicle has also been researched.

Alternative fuels may result in lower HC and CO_2 emissions than conventional gasoline. The use of alternative fuel in conventional, internal combustion engines depends on factors such as technical viability, environmental acceptability, safety, fuel economy, cost, and engine performance during different operating conditions.[52]

Table 5.22 shows environmental, performance, and cost data for different fuels. Diesel has the highest energy content (MJ/liter) among these fuels; hydrogen has the lowest. Greenhouse gas emissions are lowest for a solar-powered electric vehicle and highest for an internal combustion vehicle using methanol produced from coal.

The performance factors indicated are density, compression ratio, tank volume, and flammability limits. All alternative

TABLE 5.22. ENVIRONMENTAL, PERFORMANCE, AND COST METRICS FOR DIFFERENT FUELS

Metrics	Gasoline	Diesel	LPG	Natural Gas	Ethanol	Methanol	Liquid Hydrogen	Electric Vehicle
Environmental								
Energy (MJ/l) (Ref. 68, 81, and 82)	32	37	24	3.8	21	16	25	0.2–0.3
Life Cycle Emissions: CO_2 equivalent (g/mi) (Ref. 22)								
Operation of Vehicle	333.7	325.0	283.6	269.0	51.0	277.4	22.6	0
Fuel								
Compress/Liquefy	0	0	0	48.3	0	0	266.3	0
Fuel Distribution	5.9	5.6	6.8	17.4	19.3	29.2	1.7	7.6
Fuel Production	68.2	23.7	12.4	5.8	260.8	84.0	60.2	402.8
Feedstock Transportation	10.6	10.6	3.9	0	16.5	9.5	0.1	13.1
Feedstock Recovery	11.8	11.8	8.1	7	184.6	17.6	3.8	8.6
CH_4 Leaks/Flares	5.1	5.1	5.7	13.5	0	11.3	0	19.9
Car Assembly	14.0	10.5[1]	14.3	14.6	14.0	14.0	14.5	14.4
Materials	41.9	31.6[1]	42.8	47.6	41.9	41.9	45.2	46.6
Total	491.2	423.9	377.6	423.2	588.1	484.8	414.5	512.9
	(reformul.)		(NG and oil)	(CNG)	(corn)	(natural gas)	(nuclear)	(U.S. grid)
Life Cycle Emissions: CO_2 Equivalent (g/mi) (Ref. 68)								
Operation of Vehicle	344.5			262.0	51.0	277.4	22.6	1.3
Fuel								
Compress/Liquefy	0			51.3	0	0	0	0
Fuel Distribution	5.9			19.6	14.1	15.2	1.7	0
Fuel Production	51.2			6.5	-63.1	401.5	0	0
Feedstock Transportation	11.1			0	13.9	1.5	0	0
Feedstock Recovery	12.4			7.9	60.7	9.2	0	0
CH_4 Leaks/Flares	5.4			15.9	0	37.3	0	0
Car Assembly	14.0			14.4	14.0	14.0	14.5	14.4
Materials	41.9			43.6	41.9	41.9	45.2	46.6
Total	486.3			421.2	132.5	798	84.1	62.3
	(regular)			(LNG)	(wood)	(coal)	(solar)	(solar)
Performance (Ref. 61)								
Density (kg/l)	0.71–0.76	0.81–0.85	0.51	0.09	0.79	0.79	0.38	
Compression Ratio	9:1	15:1–18:1		15:1–18:1		12:1		
Tank Volume Gallon	20	22		98	30	41	105	
Flammability Low/ High (% Volume in Air)	0.6/8	0.6/7.5		5/15	3.5/15	5.5/26	4/77	
Cost (¢/km) , 1987 (Ref. 52)	1.7–2.1	1.3–1.7	2.3–2.8	0.9–2.0	2.4–3.7[z] 1.4–8.5[x]	1.1–2.4[y] 2.3–4.6[x]	2.8–5.6	

[1] Low values stem from the assumed long lifetime of diesel vehicles.

[x] From wood.

[y] From natural gas.

[z] From maize and wheat.

For greenhouse gas emissions, assumed vehicle gets 30 mpg combined city/highway using gasoline. All other alternative fuels are normalized to this vehicle except the electric vehicle, which is a 24.5-mpg equivalent, city driving only. Assume light-duty diesel vehicle gets 39 mpg, weighs 100 lbs more than comparable gasoline vehicle and has a useful life of 150,000 miles as compared to 108,000 miles for the gasoline vehicle.[22] For a comprehensive list of assumptions for evaluating the fuel cycle and vehicle emissions, refer to Ref. 22.

Sources: Refs. 22, 52, 61, 68, 81, and 82.

fuels have higher lean flammability limits than diesel and gasoline, thus indicating these fuels have lower fire-hazard potential than conventional fuels.

The cost metrics for different fuels show that CNG and methanol (from natural gas) have fuel costs comparable to those of diesel and gasoline. Ethanol and hydrogen are high-cost fuels. A short description of different fuels follows.

Reformulated Gasoline

Reformulated gasoline and oxygenates are included in this section, although they are not considered alternative fuels by EPA. Reformulation of fuel for internal combustion engines offers another approach to reducing vehicle pollutant emissions. In particular, fuel oxygenates have been mandated to reduce carbon monoxide emissions. The petroleum industry is beginning to market gasoline formulations that emit less hydrocarbons, nitrogen oxide, carbon monoxide, and toxics than conventional gasoline. The new gasoline can be introduced without major modification to existing gasoline vehicles or the fuel distribution system.[83]

ETBE (ethyl tert-butyl ether), MTBE (methyl tert-butyl ether), and ethanol are gasoline oxygenates currently in use in the marketplace. Most gasoline producers selected MTBE to increase oxygen content prior to the EPA mandate for the use of ethanol and other oxygenates from renewable sources. Although EPA does not have a mandate requiring the use of renewable oxygenates under the reformulated gasoline program, EPA did promulgate such a requirement. However, this requirement was successfully challenged and overturned by courts.[84] MTBE and ethanol have measurable shares of the oxygenate market; ETBE is beginning to break into the marketplace. MTBE has most of the market because of factors such as cost, regional availability, blending and distribution considerations, and production capacity.

The complexity of the reformulation problem is partially reflected in the eighteen grades of gasoline now in use. These grades correspond to three levels of octane that may contain MTBE octane enhancer, three grades that may contain MTBE as an oxygenate, and three grades that have adjusted Reid Vapor Pressures (RVP) for ethanol blending. Each of these nine grades is offered in summer and winter blends.

Major issues concerning reformulated gas include the following[68]:

- No infrastructure change except for refineries
- Probable small-to-moderate emissions reduction
- Engine modifications not required
- No energy security or greenhouse advantage

Diesel

Diesel fuel comprises middle-distillate, straight-run components from crude oil (boiling between 150 and 400°C) and streams from secondary processes such as hydrodesulfurization and cracking. Diesel fuel properties are highly dependent on the quality of the crude oil feedstock.[52]

Liquefied Petroleum Gas (LPG)

Liquefied petroleum gas (LPG) is produced mainly in the production and refining of oil and natural gas. LPG consists primarily of propane and butane, which liquefy at moderate pressure and ambient temperature and thus are convenient to store. The proportion of propane to butane varies by region. Two factors contribute to the reduced range of LPG vehicles: reduced energy content of LPG and the weight of the tanks in which LPG is stored on the vehicle. In an attempt to obtain a comparable range, larger tanks are used; thus, fuel economy is reduced somewhat.

Issues concerning LPG use in vehicles include the following[85]:

- Three-fourths the driving range of gasoline
- Refueling infrastructure is already in place because of recreational and rural use
- Development of liquid fuel injection system for propane is in progress

Natural Gas

Natural gas (NG) can be transported in the form of either compressed natural gas (CNG) or liquid natural gas (LNG). CNG vehicles are in a more advanced stage of development than LNG vehicles. To have a reasonable operating range, a CNG vehicle requires large, heavy gas cylinders. This added weight results in decreased fuel economy and performance compared to gasoline vehicles. CNG storage systems have five times the volume and weight of gasoline tanks containing the same energy. Aluminum or plastic composite cylinders for CNG are lighter but more expensive than the conventional steel cylinder.

An industry consortium headed by Johns Hopkins University Applied Physics Laboratory has developed an advanced natural gas vehicle which is being funded by the U.S. Department of Energy. Initial test results indicate a 315-mile driving range between refuelings and a fuel economy of 32 mpg. Fuel density and storage space requirements limit CNG vehicles. The Johns Hopkins design retains 75% of the original trunk space by using run-flat tires, which compensate for the absence of a spare tire and jack. These tires can be driven up to 250 miles with no air and without incurring damage.

Key issues in using natural gas as a vehicle fuel include the following[68,85,86]:

- Potential for ozone reduction but increased methane emission which contributes to global warming; also can result in higher NO_x emissions
- 10 to 20% power loss due to loss in volumetric efficiency compared to gasoline
- High octane value of methane, compression ratio can be increased to 13–14:1, thus compensating for power loss
- CNG has a driving range problem (one-fourth the energy of gasoline for a given volume even at 3000 psi)
- High initial vehicle cost for CNG
- Lean-burn technology coupled with high-turbulence combustion chamber used for natural gas can meet the new emissions regulations for heavy-duty engines
- LNG has improved driving range, but additional cost is associated with liquefaction and cryogenic storage (-258°F)
- Variation in composition of natural gas among different regions has been identified as a problem
- CNG has 0.84 times lower life cycle greenhouse emissions compared to gasoline
- Slower refueling compared to gasoline
- Currently natural gas vehicles pay little motor fuel tax at the state or federal level

Alcohol Fuels (Ethanol and Methanol)

Typical alcohol fuels are ethanol and methanol, which can be produced from natural gas, coal, and biomass such as corn and starch. The corn and ethanol industry is represented by stakeholders such as the National Corn Growers Association, American Corn Growers Association, and the Renewable Fuels Association. The MTBE lobby includes the American Methanol Institute, the American Petroleum Institute, and the National Petroleum Refiners Association. The potential for each oxygenate alternative can be analyzed according to environmental and economic factors as indicated in Table 5.21.

Ethanol can be produced by yeast fermentation from any biomass feedstock containing simple sugars, starch, or cellulose such as corn, wheat, and wood.[52] Overall energy use in the process ranges from 30 to 60% of the energy content of the ethanol produced.[87] The major limitation of ethanol is its relatively high vapor pressure when mixed with gasoline. Standards for summertime gasoline vapor pressure can restrict the use of ethanol. The EPA has concluded in the final reformulated gasoline program that ethanol containing reformulated gasoline does not result in increased NO_x emissions compared to gasoline containing either ether-based oxygenate.[84] In addition, ethanol is generally "splash" blended with gasoline prior to being transported to the filling station, whereas MTBE and ETBE can be blended at the refinery and shipped via pipeline. Important issues concerning ethanol use include[68]:

- Currently used as additives to gasoline
- Gasoline vehicles fueled with ethanol-containing gasolines have good reliability, high performance, and high fuel efficiency
- Cold starting is a problem with E100
- Organic emissions will have lower reactivity than gasoline, but higher reactivity than methanol
- Ethanol from corn has 1.23 times higher life cycle greenhouse emissions compared to gasoline
- Vehicles powered by ethanol produced from wood emit a low 133 g/mi of greenhouse gas equivalents, factoring in the carbon-fixing nature of trees; however, the adequacy of forests as a source for vehicle fuel is problematic
- Higher cost than gasoline
- One-third less range compared to gasoline

Methanol can be derived from natural gas, coal, and biomass. Methanol production from wood probably has greater long-term potential than that of ethanol from food crops.[52] All major automakers have produced cars that run on M85, a blend of 85% methanol and 15% gasoline. Cars that burn pure methanol (M100) offer much greater air quality and efficiency advantage.[83]

Issues concerning methanol use include the following[3,34,68,84,85]:

- Cold starting is a problem with M100
- Lower photochemical reactivity than gasoline and therefore tailpipe emissions have less ozone-forming potential
- High octane rating (110 RON), compression ratio (12:1), and wider flammability than gasoline; allows methanol engine to be operated at leaner air-fuel ratio than gasoline engines, promoting higher fuel efficiency and lower CO and HC emissions
- Abundant natural gas or coal feedstock
- As much as one-half lower range compared to gasoline
- Formaldehyde emissions are a problem
- More toxic than gasoline
- Under normal vehicle operating temperatures, the air-to-vapor ratio in a fuel tank results in a flammable mixture when methanol is used. This mixture will not explode spontaneously in the absence of an ignition source. The methanol vehicle is designed to prevent the possibility of an ignition source in the fuel tank. Furthermore, given the cooler burning properties of methanol, no explosion would result if a fuel tank fire occurred.
- Costs are likely somewhat higher than gasoline, especially during the transition period
- Lower volatility, compared to gasoline, results in reduced evaporative emissions
- Methanol use results in significantly higher formaldehyde emissions than gasoline, which is a cause of concern in enclosed spaces
- Methanol from coal has 1.72 times higher life cycle greenhouse gas emissions than gasoline

Hydrogen

Hydrogen can be produced from fossil fuels, biomass, electricity, water, methanol, or other fuels. Today, most hydrogen is produced from natural gas by reformation at efficiency of 70 to 75%.[88] The cost of this hydrogen is two to three times that of feedstock.[89] Electrolysis of water to produce hydrogen has an efficiency of 75% and is extremely expensive, \$45–55/10^6 Btu. Hydrogen production from coal gasification has an efficiency of 60–65% and is projected to be least expensive.[88,89]

Hydrogen has a high energy content per kilogram but low volumetric energy density, as shown in Table 5.22. Therefore, the fuel tank for a current conventional vehicle powered with hydrogen must be bulky and heavy, which reduces fuel economy. Hydrogen fuel for automobiles can be stored onboard as a gas in pressure vessels at approximately 200 bar, as a cryogenic liquid at -253°C in a dewar vessel, or chemically bonded in metal hydride. Hydrogen is extremely flammable, and a pure hydrogen flame cannot be seen by the naked eye. Even in the best insulated storage containers, some liquid hydrogen evaporates. Losses can range from 0.5 to 3% of stored fuel per day, creating a potential safety hazard.[52]

Issues concerning hydrogen use in automobiles include the following[89,90]:

- Currently hydrogen is delivered by truck or rail as a high-pressure compressed gas or liquid, because the demand is well below that needed to justify a pipeline. Hydrogen transport through pipeline has other disadvantages such as embrittlement of steel pipeline by pure hydrogen and a high-pressure requirement in the pipeline because of the low volumetric energy density of hydrogen.
- Onboard storage of hydrogen remains a challenge. Hydrogen gas has one-third energy density of natural gas, and liquid hydrogen has one-quarter energy density of gasoline. To store the equivalent of 19 liters (5 gallons) of gasoline as compressed hydrogen requires a heavy tank larger than a 200-liter drum. Hydrogen liquefies at 20 K, requiring energy-intensive compression and refrigeration.
- Hydrogen also can be stored as a solid in metal hydrides. Metal hydrides suitable for automotive application typically store 0.5 to 2% of hydrogen by weight, and the storage is large and heavy. The hydride suitable for automotive application is FeTi, which releases hydrogen at the engine exhaust temperature and has low hydrogen-storage capacity. Energy penalty is considerably higher for hydride storage, making the fuel more expensive compared to liquid hydrogen.
- Hydrogen engines can run at higher compression ratios and therefore have higher efficiency (15 to 20%) and power compared to gasoline engines. However, the low energy density of hydrogen leads to a reduction in power for a given displacement, compared with gasoline. Hydrogen has low quenching distance and therefore can reduce wall quenching loss compared to gasoline. The higher combustion temperature of hydrogen causes higher thermal losses, combustion noise, and NO_x emissions. (NO_x emissions can be controlled by extremely lean operation that takes advantage of the wide flammability limit of hydrogen.) Hydrogen-operated piston engines are prone to knocking and may result in backfiring into the intake manifold because of hydrogen's low flashback limit. Previous research on hydrogen concentrated on converting the gasoline engine for hydrogen application. An engine optimized specifically for hydrogen has not yet been designed. Thus, despite all the disadvantages of hydrogen, the operation of the internal combustion engine on hydrogen itself is not a serious impediment compared to its availability, distribution, and onboard storage.
- Hydrogen can be used to produce electricity by electrolysis with oxygen in a fuel cell. The attraction of fuel cells arises from zero tailpipe emissions and high thermal efficiency (70 to 90%) unconstrained by the Carnot cycle, unlike all heat engines.
- Although hydrogen has wide flammability and explosion limits and high diffusivity, experts claim that safety issues can be maintained through installation of proper sensors and training.
- Table 5.23 shows that hydrogen internal combustion engine vehicles (ICEVs) are less efficient in primary energy use than gasoline and natural gas ICEVs or battery EVs. Hydrogen ICEVs have no significant advantage and most have the disadvantage of greenhouse gas emissions when the hydrogen is produced from fossil fuels. The tailpipe emissions of the hydrogen ICEVs are ultralow but not zero because of NO_x emissions.
- With optimistic assumptions, hydrogen fuel cell vehicles are projected to be as energy efficient as battery EVs at today's 33% electrical generation efficiency. The battery EVs and the hydrogen fuel cell vehicles using compressed hydrogen are projected to

TABLE 5.23. PRIMARY ENERGY USE AND CO_2 EMISSIONS FROM DIFFERENT VEHICLES[89]

Primary Source	Vehicle		Primary Energy, Kcal/km	CO_2 Emissions, g/km
Gasoline	ICE		580	164
Natural Gas	ICE		570	175
	Battery EV		492	110
	Hydrogen ICE			
		Compressed (R)	742–807	1581–173
		Hydride (R)	872–925	169–183
		Liquid (R)	1027–1116	228–248
		Compressed (E)	2086–2269	465–508
	Hydrogen Fuel Cell			
		Compressed (R)	486	96
		Liquid (R)	713	160
		Compressed (E)	1368	465
Coal	Battery EV		492	254
	Hydrogen ICE			
		Compressed (G)	927–1008	508–555
		Hydride (G)	1090–1156	584–634
		Liquid (G)	1182–1283	615–668
		Compressed (E)	2086–2269	1080–1173
	Hydrogen Fuel Cell			
		Compressed (G)	608	336
		Liquid (G)	821	426
		Compressed (E)	1368	708

(R) By steam reforming.
(E) By electrolysis.
(G) By gasification.
Energy and CO_2 are reported for fuel production and vehicle operation stage.

have the lowest greenhouse gas emissions—approximately half those of gasoline.
- Hydrogen from solar power has 0.056 times lower life cycle greenhouse emissions, and hydrogen from nuclear power has 0.82 times lower life cycle emissions as compared to gasoline.
- Because of the high cost of water electrolysis, hydrogen from nonfossil sources is anticipated to be competitive with that derived from natural gas only after the year 2020.

5.3.4 Alternative Vehicles

A range of alternative vehicles and programs to support their advancement exists in varying stages of development. Electric vehicles have been researched for several decades, while hypercars are between concept and prototype stages. Alternative vehicle initiatives have been led by individual OEMs, U.S. Council for Automotive Research (USCAR), and other research institutions such as the Rocky Mountain Institute.

Partnership for a New Generation of Vehicles

The Partnership for a New Generation of Vehicles (PNGV) is an important, recently initiated program for dramatically improving vehicle fuel economy. PNGV is a cooperative, collaborative research and development program between the U.S. government and USCAR, which is composed of the Big Three automakers: Chrysler, Ford, and General Motors.[46] As a recent publication from PNGV states[91]:

> PNGV's long-term goal is to develop vehicles that will deliver up to three times greater fuel efficiency (80 miles per gallon or Btu equivalent) and cost no more to own and operate than today's comparable vehicles (i.e., the 1994 Chrysler Concorde, Ford Taurus, and Chevrolet Lumina). At the same time, this new generation of vehicles should maintain the performance, size, and utility standards of today's vehicles and meet all mandated safety and emission requirements. The development of energy-efficient, low-emission vehicles is important for both economic and environmental reasons. From an economic viewpoint, the introduction of a new, marketable generation of vehicles may improve U.S. competitiveness in the global automotive market. On an environmental level, a new generation of fuel-efficient vehicles promises benefits such as a reduction in the volume of exhaust emissions, which will improve air quality and public health, and reduced gasoline consumption.

To achieve a fuel economy of 80 mpg, the program has targeted three areas for improvement:

- Converting energy more efficiently
- Implementing regenerative braking to recapture energy
- Reducing the energy demand for the vehicle

More specifically, the program states that 80-mpg vehicles must meet the following design standards[46]:

45% thermal efficiency
30% mass reduction
60% regenerative braking efficiency
90% efficient energy storage
20% power drag
20% power rolling resistance coefficient
30% more efficient accessories

Specific conditions related to the up-to-three times fuel-efficiency goal are as follow:

- Use an efficiency metric of miles per equivalent gallon of gasoline. If an alternative source of energy is used, the goal will be miles per Btu equivalent of a gallon of gasoline (or 114,132 Btus). (Also, it is assumed that use of an alternative energy source will require separate government/industry activities and direction regarding Btu measurement and infrastructure challenges.)
- Design to Tier 2 emissions at the default levels of 0.125 HC, 1.7 CO, and 0.2 NO_x at 100,000 miles while complying with other Clean Air Act requirements.
- Meet the up-to-three-times efficiency improvement goal while meeting present and future FMVSS standards, and while meeting equivalent in-use safety performance of the target vehicles.
- Achieve a recyclability objective of at least 80%, up from 75% industry average today.
- A concept vehicle should be available in approximately six years and a production prototype in approximately ten years.

Specific criteria regarding performance and utility for the comparable family-sedan vehicle include:

- Acceleration of 0 to 100 kph (0 to 60 mph) in 12 seconds (at curb weight, with 300 lbs of passenger and full fuel tank).
- Luggage capacity (475 liters, or 16.8 cubic feet) and load-carrying capacity to be the equivalent of these sedans (load-carrying capacity includes up to six passengers with full fuel tank and 200 lbs of luggage).
- Operating metro-highway range of at least 610 kilometers (380 miles) on the 1994 Federal Drive Cycle.
- Equivalent to comparable 1994 family sedans in all of the following aspects:

  Performance in all aspects, including acceleration, cruising speeds, gradeability, and driveability at sea level and at altitude
  Ride and handling
  Noise, vibration, and harshness control
  Customer features and options, including climate control and entertainment packages
  Total cost of ownership (with nonpreferential tax treatment on a Btu basis) adjusted for economic factors

- Useful life of 160,000 km (100,000 miles) at minimum, comparable, or improved service intervals and refueling time.
- To be easily produced for export and sale in major world markets.

Electric Vehicles

Electric vehicles (EVs) are being promoted as a clean alternative to internal combustion engine vehicles (ICEVs). EVs have been referred to as zero-emission vehicles. While mobile pollutant emissions are essentially eliminated in EVs, air pollutant emissions are shifted back to the point of electric power production. Both energy and emissions throughout the vehicle life cycle must be analyzed in comparing the future sustainability of EVs to ICEVs and other emerging technologies. In addition to environmental factors, several performance factors may limit widespread implementation of electric vehicles. Currently, limited driving range and battery weight and size are important vehicle design obstacles.

The U.S. Advanced Battery Consortium, which was formed in January 1991, is a USCAR initiative. The mission of this consortium is "to pursue research and development of advanced energy systems capable of providing future generations of electric vehicles with significantly increased range and performance." Technologies that are currently being researched include lead-acid, nickel-cadmium, sodium-sulfur, and nickel-iron batteries.

Life cycle energy studies do not indicate a clear advantage between electric vehicles and internal combustion vehicles. The energy consumption of each system can be compared by computing the fuel production energy and use phase energy requirements. Electric motors are highly efficient in converting electrical energy into mechanical energy, but the generation of electricity from primary sources is approximately 32% efficient for the U.S. grid. For electric vehicles, use phase energy is estimated from the driving range and the battery charging requirements. For example, the Ford Ranger has a reported range of 58 miles without A/C or heater operation and a battery energy capacity of 23 kWh. Using an efficiency of 32% to convert primary energy into electricity and using a conversion of 126,000 Btu/gal of gasoline, the Ranger has an equivalent fuel economy of 35.9 mi/gal. Table 5.24 presents specifications provided by Ford for two prototype electric vehicles, the Ecostar (Escort Van) and the 1998 Ford Ranger EV.

EVs powered by most battery types currently have a limited driving range relative to ICEVs, which is substantially reduced by heating and cooling loads, as shown in Table 5.22. At 32°F and with the heater operating, range is reduced to 35 miles and fuel economy drops to 21.7 mpg of gasoline equivalents.

Current EVs typically have a range of less than 100 miles. However, a range of 238 miles was recently reported for the GM Ovanic LLC, an EV powered by a nickel-metal hydride battery.[92]

Several other comparisons of energy efficiency have been made between ICEVs and EVs. Wang and DeLuchi[93] analyzed ICEV and EV energy consumption using four primary energy sources: petroleum, natural gas, biomass, and coal. They calculated the energy consumed in the production of gasoline from biomass and coal in addition to a petroleum feedstock. Two scenarios were studied based on conditions for the years 1995 and 2010. They found that 1995 EVs required 8 to 30% more energy relative to a petroleum-powered ICEV when coal, petroleum, or NG is used as the primary energy source for electricity. For the year 2010 scenario, which assumed improvements in EV design and power plant conversion efficiencies, EVs relative to gasoline ICEVs would reduce their primary energy

TABLE 5.24. TWO PROTOTYPE ELECTRIC VEHICLES FROM FORD

	Ecostar	Ranger EV
Battery Type	Sodium-sulfur	Sealed lead-acid
Payload	1000 lb	700 lbs
Maximum Power	50 kW	23 kWh
Recharge Time, from 20% (240 V, 30 amp)	6–7 hrs	NA
Acceleration (0–50 mph)	11.1 s	<14 s
FUD* Cycle (without A/C or heater operation)	100 mi	58 mi
Customer Range (@ 32°F including heater)	NA	35 mi

* FUD - Federal Urban Driving Cycle.

consumption by 7 to 20% if the primary source were petroleum, 15 to 27% for natural gas, and 17 to 29% for coal. For biomass, EVs would increase primary energy consumption by 6 to 23%.

Riley calculated use phase energy consumption for EVs and ICEVs.[68] Energy consumption for these vehicles is provided in Table 5.25. Life cycle energy was obtained by adjusting use phase figures to account for primary energy production efficiencies for electricity (32%) and gasoline (83%).

These data should be evaluated cautiously because they do not represent functionally equivalent vehicles or driving cycles.

Energy allocation for EVs and ICEVs also was analyzed by Riley.[68] He reported the following operating efficiencies for electric and internal combustion engine vehicles:

	Electric	Spark Ignition
Engine	80%	23%
Drivetrain	82%	78%
Battery, Charger	70%	
Total Vehicle	46%	18%

Using these figures, overall vehicle operating efficiencies would be an almost identical 14.7% for an EV and 14.9% for an ICEV.[68] However, with the shaft efficiency of 12.6% provided by PNGV, overall vehicle operating efficiency for ICEVs would be 10.5%.

Regenerative braking provides a means to recover kinetic energy that is typically dissipated as heat in conventional vehicles during deceleration. A portion of the kinetic energy is captured and used to charge the battery. Testing on the General Electric/Chrysler ETV-1 indicated that approximately 42% of the kinetic energy was captured to charge the battery; however, this does not consider charging efficiency. Riley[68] reports that, in practice, regenerative braking normally increases the range of the vehicle by 5 to 15%. However, he noted that for the GM Impact, the range was increased by 25% through regenerative braking.

TABLE 5.25. ENERGY CONSUMPTION FOR ELECTRIC AND CONVENTIONAL VEHICLES

Vehicle	Weight, kg	Driving Cycle	kWh/mi or km/l	kJ/km Use Phase	kJ/km Life Cycle
Impact	1321	City[a]	0.298	669	2091
TEVan	2663	City[a]	0.680	1508	4713
Four-Seat BMW	1634	ECE[b]	0.446	998	3119
ETV-1	1780	FUDS	0.486	1088	3400
1990 U.S. CAFE		FUDS	12	2916	3513
1990 Geo Storm	908	FUDS	22.5	1555	1873
Hypothetical	450	City[c]	32	1093	1317

[a] Random urban driving cycle.
[b] A composite of the Federal Urban Driving Schedule (FUDS) and Federal Highway Schedule.
[c] Estimated urban driving cycle.
Source (except for life cycle calculations): Ref. 68.

The cost of electric vehicles also is a potential barrier for successful implementation. The Ecostar has a list price of $100,000, although this would be lowered considerably if it were mass produced.

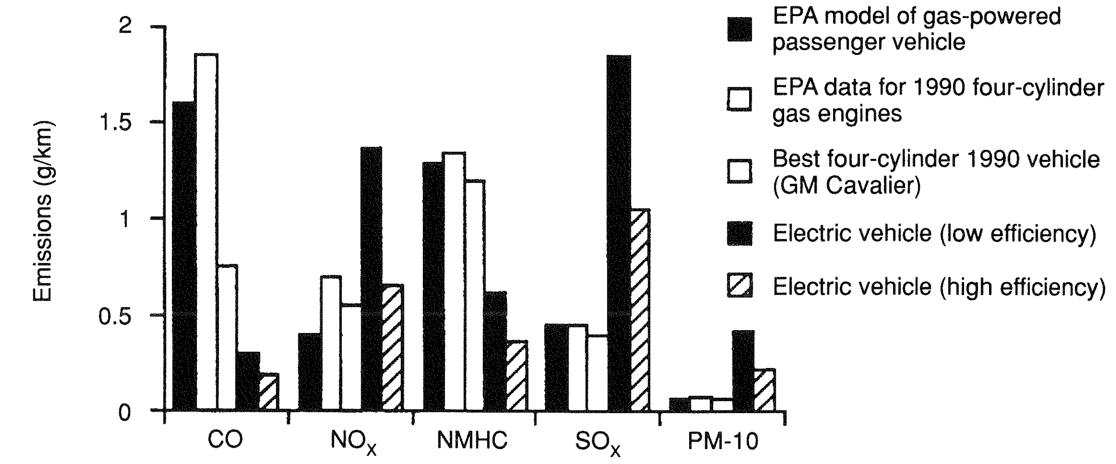
Most studies indicate that electric vehicle use will dramatically reduce emissions of carbon monoxide and nonmethane hydrocarbons.[22,94] Emission factors for electric power generation depend on the primary energy source and power plant control technologies. Figure 5.9 shows life cycle air pollutant emissions for ICEVs and EVs. Sulfur dioxide emissions are greater for EVs because of the sulfur impurities in coal, which accounted for 56% of U.S. electricity generation in 1992.[8] One advantage often cited for EVs is that stationary sources may be more effectively controlled than mobile sources.

A comparison of greenhouse emissions depends directly on the power-train efficiencies for each system. A comprehensive study by DeLuchi[22] indicated that electric vehicles (513 g/mi CO_2 equivalents) generated slightly higher life-cycle greenhouse gas emissions relative to gasoline vehicles (491 g/mi CO_2 equivalents).

The U.S. Department of Energy is conducting a comprehensive study of the total energy cycle of EVs. A comparative assessment of emissions and residuals for EVs and conventional vehicles is being performed jointly by the National Renewable Energy Laboratory, Argonne National Laboratory, and Pacific Northwest Laboratory.

A major challenge for the U.S. Battery Consortium is to develop a battery with sufficiently high energy density and power density using nonhazardous materials. Gasoline stores more than 300 times the energy of the same weight of a conventional lead-acid battery, assuming a 40 W/kg energy density for the battery. This energy density ratio is reduced by a factor of four to five when the higher efficiency of an electric drivetrain over a gasoline-based drivetrain is accounted for in the comparison.

Battery technology is critical to the future of electric vehicles. Presently, lead-acid batteries are the only mature affordable technology.[85] A typical power requirement for vehicle operation at 50 mph is approximately 8 kW. Heating requirements can be as high as 5 kW; cooling requirements in hot environments are approximately 3.5 kW.



NMHC = nonmethane hydrocarbons; PM-10 = particulates <10 μ

Fig. 5.9 Life cycle emissions for EVs and ICEVs. (Source: Based on research conducted by D. Moody, National Pollution Prevention Center, using data from Refs. 95 and 96.)

The ideal battery has both a high power density as well as energy density. The power density is required for acceleration and operation of accessories. The energy density will determine the range of the vehicle.

Lave *et al.*[97] compared the environmental releases of lead from the production of lead acid batteries for electric vehicles with lead emissions for a comparable car burning leaded gasoline. They found that lead releases from EVs were 60 times greater than the comparable ICEVs using leaded gasoline. Based on these findings, they challenged the environmental benefits of electric vehicles. However, more recent data indicates that they substantially overstated the lead releases from battery production.[98–100]

A recent review of energy and environmental impacts of electric vehicle battery production and recycling for several alternative battery technologies was conducted by Gaines and Singh.[101] Energy and recycling data are provided in the following list:

Advanced Lead-Acid	Lifetime is up to 80,000 miles Low energy density 50 Wh/kg 25 kWh weighs 500 kg Currently 90% of the lead and lead oxides from batteries are recycled or exported for recycling
Nickel-Cadmium	Has a life of 2000 cycles which would last six to ten years 57 Wh/kg 25 kWh Ni-Cd battery weighs 439 kg In the United States, Ni-Cd batteries are being recycled by INMETCO, which uses a pyrometallurgical process to produce ingots of alloying elements for use in stainless steel manufacture
Sodium-Sulfur	Operates at a high temperature (at least 300 to 350°C) Has a life of 1000 cycles 80 to 200 Wh/kg 25 kWh @ 100 Wh/kg weighs 250 kg Recycling is not yet economical; retired batteries are incinerated
Nickel-Metal-Hydride	Currently in production on a small scale (1000 packs expected to be produced in 1997) but capable of larger production volumes if demand by automotive industry increases[102] Battery life uncertain 70 to 80 Wh/kg 25 kWh weighs 330 kg INMETCO can recover Ni, Fe, Cr, and Mn as alloying elements

Fuel Cell Vehicles

Fuel cells, which remain in the research and development stage, are an important alternative to internal combustion engines. Chemical energy is converted directly into electrical energy using fuels such as hydrogen, methanol, and methane. In particular, fuel cells are environmentally attractive because in these electrochemical devices hydrogen and oxygen (from air) react to produce heat, electricity, and water. Conversion of fuels such as methanol and methane to hydrogen also will produce carbon dioxide and/or trace amounts of carbon monoxide. Current fuel cell technologies under development include the phosphoric acid fuel cell (PAFC), proton exchange membrane fuel cell (PEMFC), solid oxide fuel cell (SOFC), and direct methanol fuel cell (DMFC). The PAFC is the more mature technology and has been demonstrated in 200-kW power plants. The PEMFCs can achieve the power density necessary for automotive applications, but cost must be reduced and performance factors such as response rate and start-up time must be improved. High operating temperature is a major limitation for SOFC.

GM is heading a $35.2-million, 30-month project funded by the U.S. Department of Energy to further develop a methanol-based, proton-exchange membrane (PEM) fuel cell. The first stage of this device consists of a methanol processor that produces hydrogen by reforming methanol with steam. This reaction occurs at 275°C and uses a copper oxide/zinc oxide catalyst. In the second stage, hydrogen feeds into the fuel cell and produces direct current and water. Carbon dioxide is a contaminant in the hydrogen feed, which can diminish the cell's power output. GM indicates that the PEM fuel cell delivers a higher power density than competing phosphoric acid cells. One limitation of this device is the high cost of the noble metals that serve as catalysts.[103]

Hybrid Drives

Hybrid vehicles are classified into two basic configurations: series and parallel. In the series configuration, a heat engine drives a generator that either charges batteries or directly powers the motor to reduce battery load. For the parallel hybrid design, the vehicle is propelled independently or simultaneously by an internal combustion engine and an electric motor. Although the series configuration is mechanically simpler, the parallel configuration offers greater performance flexibility.[68] However, greater reliance on internal combustion may result in lower fuel economy and higher emissions.

Hybrid drives combine two different drive components in a way that maximizes the advantages of each under varying road-load conditions, thus achieving performance benefits which outweigh increased production costs. Typical storage devices for hybrid drives are ultracapacitors, flywheels, batteries, and fuel cells. These storage devices are used to recapture energy during braking and generate additional power for peak requirements such as climbing hills and rapid acceleration. Hybrid drive systems that combine an internal combustion engine and electric drive have the near-term potential of being an alternative to conventional gasoline-driven automobiles for the following reasons:

- The current internal combustion engine drivetrain does not efficiently match the road load requirements under all driving conditions. This leads to a drop in efficiency at part load and a resultant increase in emissions. In a hybrid drive system, the internal combustion engine can operate in its maximum efficiency regime, whereas the alternative electric or flywheel drive can efficiently operate during partial load.
- Fuel economy for a state-of-the-art series hybrid vehicle over the Federal Urban Driving Schedule and Federal Highway cycles has been found to be greater than a conventional ICEV.[104] However, a life cycle comparison of the hybrids and conventional vehicle has not been performed.

Hypercars

The Rocky Mountain Institute[62,65,105,106] advocates the development of a new class of vehicles that combines an ultralight design with a hybrid propulsion system. This combination, called a hypercar, is estimated to increase a car's efficiency by a factor of ten. Energy savings are realized for two reasons. First, ultralight vehicles have few losses caused by aerodynamic drag and rolling resistance, and the hybrid-electric drive recovers most braking energy currently lost as heat. Second, this new design is expected to benefit from secondary weight savings. Eliminating 1 kg of weight from components can lead to a 1.5 kg overall weight reduction because of lighter material requirements for the structure and suspension. Secondary weight effects are further amplified in the case of an ultralight vehicle if power steering, power brakes, and cooling become unnecessary.

New ways to design, manufacture, and sell cars can make them ten times more fuel-efficient, and at the same time safer, sportier, more beautiful and comfortable, more durable, and probably cheaper. This is the biggest change in industrial structure since the microchip.[107]

The hypercar concept uses a "leapfrog" in technology, rather than the classical approach of incremental change, and embodies four key traits:

- Thinking about components rather than systems
- Exploring incremental rather than radical changes to those components
- Thinking from the engine toward the wheels, the direction in which the energy flows
- Supposing that the needed improvements will be mainly in the efficiency of converting fuel into wheelpower via better engines and drivetrains, rather than in improving the basic physics of the platform so it requires less wheelpower

Such leapfrog technology can result in substantially better fuel economy than either continued incrementalism or the PNGV program.[65] The hypercar concept is based on redesigning the car from the wheels rather than from the engine, because approximately five to seven units of fuel are needed to deliver one unit of energy to the wheels. That huge leverage, achieved by avoiding successively compounding losses between fuel and wheels, is key to the hypercar's efficiency.

Several aspects of life cycle environmental burden and cost for hypercars are discussed below.

Material Production

Weight reductions can be achieved through the use of light materials such as aluminum, magnesium, and plastic-reinforced composites. The material composition of an average 1994 car weighing 1439 kg and a 1998 hypercar weighing 482 kg is shown in Figure 5.10. Conservative estimates suggest that even an unsophisticated early hypercar should contain only half the embodied energy of a typical production car today.[106]

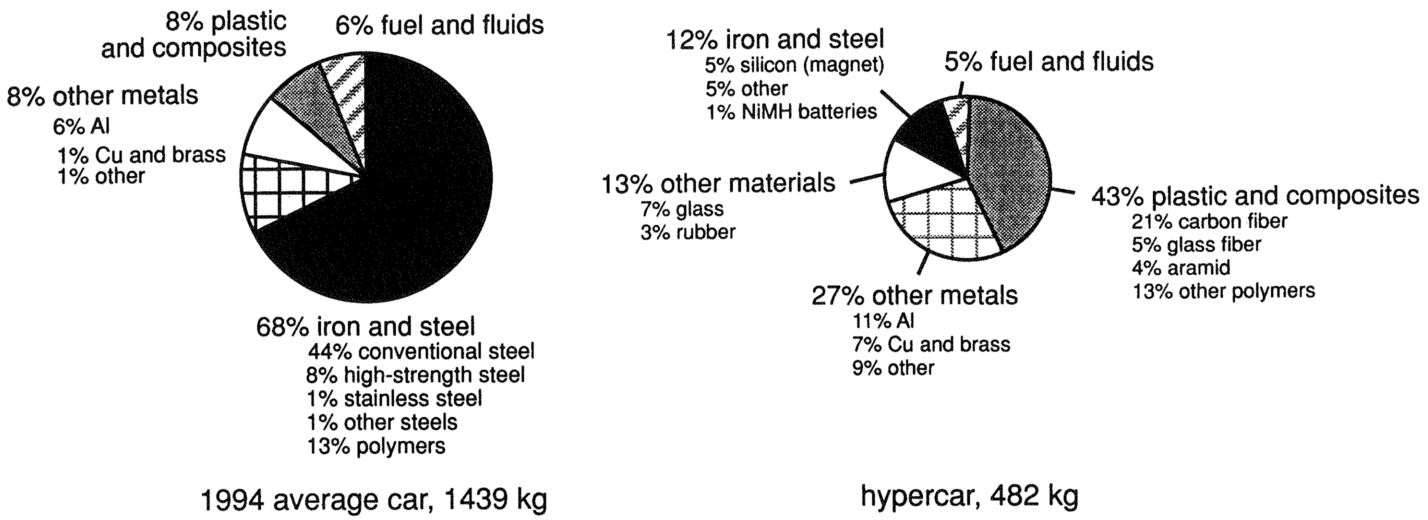


Fig. 5.10 Material composition of current average automobile and hypercar. (Source: Ref. 106.)

Manufacturing

The BIW of a hypercar probably will be a monocoque made by molding advanced polymer composites into a small number (2 to 20) of relatively large parts minimized by integration and joined by adhesives. Its materials and manufacturing methods are relatively unfamiliar to automakers whose metal-forming skills have evolved over almost a century. Hypercar manufacturing is based on the following hypothesis[108]:

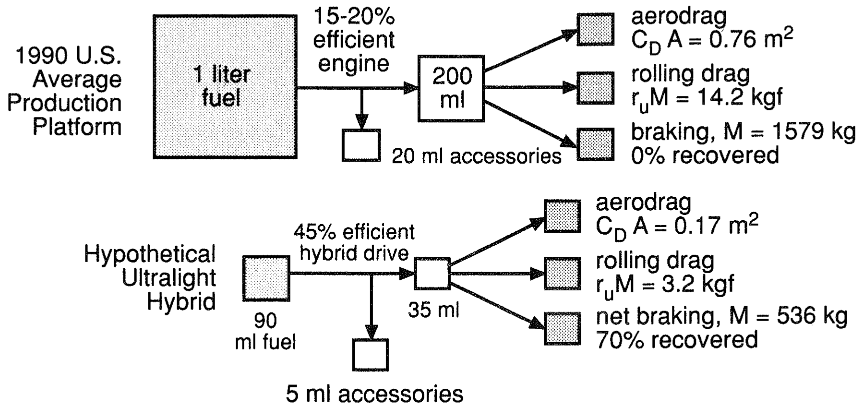
- Several-fold fewer kilograms of a typical advanced fiber than of steel are needed for the same strength
- Much cheaper fibers may be usable or even preferable for many reinforcing applications
- Utterly different manufacturing processes for composite forming can save tooling, equipment, and assembly costs
- In-mold coloring of composites can save cost compared to conventional spray painting
- A streamlined market structure for hypercars (direct sales, zero inventory, just-in-time manufacturing, direct delivery, on-site maintenance) can greatly reduce markups, thus potentially permitting a lower retail price and higher profit margin even if total production costs were somewhat higher than the conventional car

Use

The hypercar concept uses ultralight, aerodynamically slippery construction with a hybrid-electric drive. This results in a fuel efficiency increase of five- to twenty-fold compared to conventional automobiles and a reduction in pollution of one-hundred- to one-thousand-fold.[105,106] Lovins suggests that hypercar designs are expected to achieve these goals while meeting all necessary performance standards.

Figure 5.11 shows the energy required to drive 12 km in urban conditions for an average 1990 U.S. automobile and one version of a hypercar. It can be seen that the hypercar uses only 90 ml of fuel in 12 km, compared to 1 liter for the average car. However, this relationship changes in highway driving because of substantially increased drag at highway speeds and less braking energy recovery.

Ultralight, hybrid construction has a very unusual property. Ultralight construction alone typically improves fuel efficiency by a factor of 2.0 to 2.5. Hybrid-electric drive alone typically yields only a 1.3 to 1.5 factor gain. Together, both can boost fuel efficiency by a factor of 5 to 20—roughly five- to tenfold using the best commercially available ingredients or ten- to twenty-fold using state-of-the-art technologies currently under laboratory development. A fivefold improvement over typical new U.S. production cars would require only demonstrated and commercially available technologies such as fiberglass-composite construction, high-performance motor systems, conventional buffer batteries, and small gasoline engines.



Efficiency of hypercar falls on highway because drag rises as V
and less energy recovered in braking

Fig. 5.11 Two ways to drive 12 km in the city. (Source: Ref. 65.)

Two performance issues that should be addressed during prototype development are listed below:

- The propulsion system of the hypercar would not generate the same magnitude of waste heat; therefore, heating the cabin would either require additional energy inputs or a better insulated cabin that significantly reduces heat loss.
- Issues of road stability and safety must be researched through prototype testing. Road stability and traction in winter weather could pose challenges to the hypercar design.

Service

Hypercars would need an order of magnitude less consumable fluids than today's cars. In particular, motor-oil heavy metal and other troublesome contaminants would be greatly reduced or eliminated. The need for spare parts and repair also could be reduced by employing life-extending design strategies.

Retirement

Except for the dismantling stage, the hypercar cannot be reprocessed by the current car-recycling infrastructure. However, several options for end-of-life management have been proposed:

- Life extension and even reincarnation, taking advantage of the car's software, color skin, and other options for upgrades and personality change
- Reuse and remanufacturing
- Primary recycling that recovers valuable composite fibers
- Secondary recycling by grinding into filler material
- Tertiary recycling by pyrolysis for monomeric and energy value

Implementing these strategies would require additional research, and their feasibility would be limited by economics. However, preliminary analysis indicates that relative to current designs, hypercars would present less environmental burden on retirement.

Cost

Lovins and Brylawski[106] estimate that, with a carbon fiber cost of approximately $12/kg, hypercars could have a lower manufacturing cost than a standard steel unibody. In late 1994, bulk carbon fiber cost $18–22/kg ($8–10/lb). Carbon fiber cost is projected to fall to $6.6/kg ($3/lb) when production increases on the order of 5 to 10 gigagrams per year.[106] This is below the roughly $12/kg level that Big Three studies confirm should closely match or undercut steel at any production volume, even if carbon-fiber composites required painting. Even at the current price of $18/kg, their calculations indicate that a carbon fiber BIW has a lower life-cycle cost than a steel unibody at production volumes below 75,000 units per year.

5.3.5 Safety

A major challenge for introducing alternative vehicles with conventional vehicles is to overcome several safety concerns. The nation's highways are already a mix of small and large vehicles, with conventional automobiles operating beside heavy-duty trucks and motorcycles. Society also accepts the safety risks associated with bicycles riding beside automobiles on secondary roads and in cities.

From a systems perspective, safety should address not only the driver and the passenger, but pedestrians and bicyclists during operation of the vehicle. The broader life cycle systems perspective also would address safety risks for a particular vehicle design to individuals in other life cycle phases such as production workers.

Riley[68] recently reviewed safety issues surrounding low-mass cars. Factors that influence safety are human behavior, operating environment, vehicle crashworthiness, and crash survival systems. Major findings reported by Riley that are relevant to alternative vehicle design are provided below:

- Cars built in 1994 are four times safer than vehicles built in 1969, although they are approximately 10% smaller and 20% lighter.
- Alternative vehicles can be designed for specialized driving such as commuting or urban driving, thereby avoiding some safety issues related to highway driving.
- Driver risk-taking increases in proportion to vehicle mass, with the drivers of the largest cars driving the most aggressively.
- In the United States, the smallest cars are involved in pedestrian deaths at about half the rate of the largest cars.
- The accident rate for Kei cars was found to be 15% lower than for regular-size cars in Japan. (Kei cars are a small-car classification that includes vehicles with engines of up to 660 cm^3 displacement and curb weight of 1300 lbs or less, and fuel economy ranges from 50 to 60 mpg.) Since this study was conducted in 1982, this trend has reversed; the accident rate for Kei cars has increased by 25%, while the rate for regular-size cars is virtually identical.
- Pedestrians were found to have a 1.5 times greater chance of surviving an encounter with a Kei car.
- The gap between small- and large-car accident casualties is closing. 1976 to 1978 cars weighing 2000 lbs or less had a fatality rate 3.5 times higher than cars weighing 4000 to 4500 lbs. For cars in the 1986 to 1988 model years, the differential was 2.5.
- Approximately 60% of vehicle occupants now wear seat belts; wearing seat belts reduces the number of fatalities in half.
- Fatalities are approximately double for unrestrained occupants compared to occupants wearing seat belts.

The safety implications of weight reduction have been heavily debated and often show conflicting results. Historically, deaths per VMT have decreased continuously from approximately 10 deaths/100 million VMT in 1945 to approximately 2 deaths/100 million VMT in 1990.[109] However, it is difficult to disentangle the relative importance of the different factors contributing to this improvement in safety. Crandall and Graham[110] reviewed several studies of automobile safety and estimated that a 500-lb (or 14%) reduction in the average weight of 1985 cars is associated with a 14 to 27% increase in occupant fatality risk. Automobile-related risks involve drivers, passengers, pedestrians, and bicyclists. Although a heavier car may offer more protection for the driver in a single-car crash into a roadside obstacle, the heavier car may cause more injury to bicyclists, pedestrians, and drivers of a smaller car. The issue of safety versus environmental burdens is a challenging tradeoff to evaluate.

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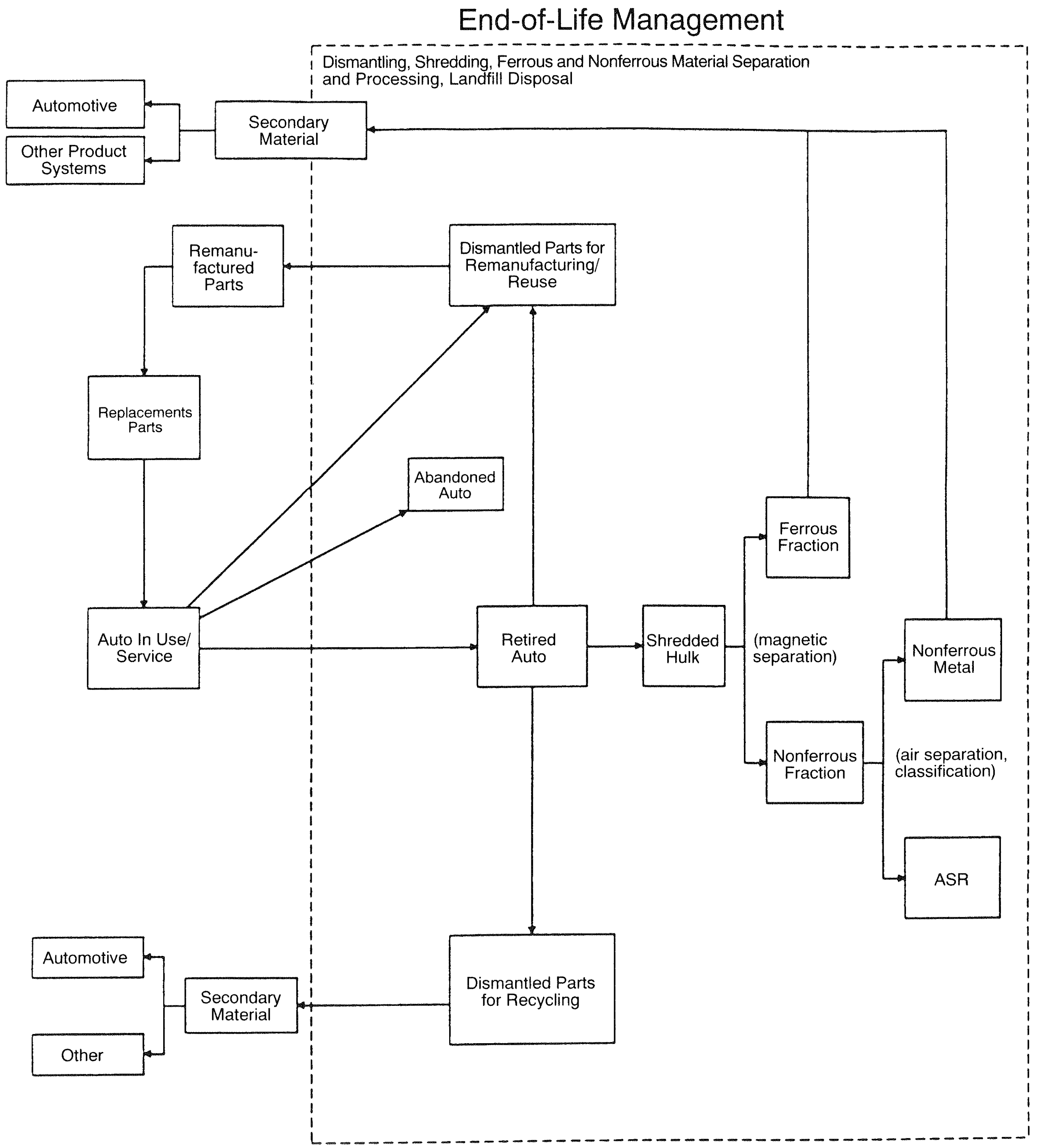


Chapter 6

End-of-Life Management

Automobile owners retire their vehicles for a variety of reasons, such as poor reliability of parts and components, degraded performance, and loss of structural integrity from corrosion or an accident. The decision to retire a vehicle poses a challenging resource optimization problem from environmental and economic perspectives. Investment of additional resources in the form of parts and components can potentially extend the life of the vehicle, but the environmental performance of an old vehicle in terms of fuel economy and emissions is worse than a new vehicle. The depreciated value of the vehicle and the owner's opportunity cost for making repairs are economic factors influencing this decision. Guidelines to assist users in making environmental tradeoffs are difficult to develop.

The material flow from retired vehicles is affected by the vehicle retirement rate, the composition of vehicles being retired, and the technology and infrastructure in place. The number of vehicles retired in a given year depends on factors such as economic conditions and the average age of vehicles on the road. Table 6.1 shows the number of motor vehicles retired annually between 1983 and 1993.

The average age of vehicles on the road has steadily increased since 1970. In 1992, the mean age of the vehicle population was 8.1 years, compared to 5.5 years in 1970. Oak Ridge National Laboratory estimated that the median lifetime of passenger vehicles in 1990 was 11.77 years and 16.05 years for light trucks.[2] These figures were derived from scrappage and survival rates. Lifetime mileage is estimated at 100,500 miles.[2]

TABLE 6.1. MOTOR VEHICLES RETIRED FROM USE (THOUSANDS), 1983–1993

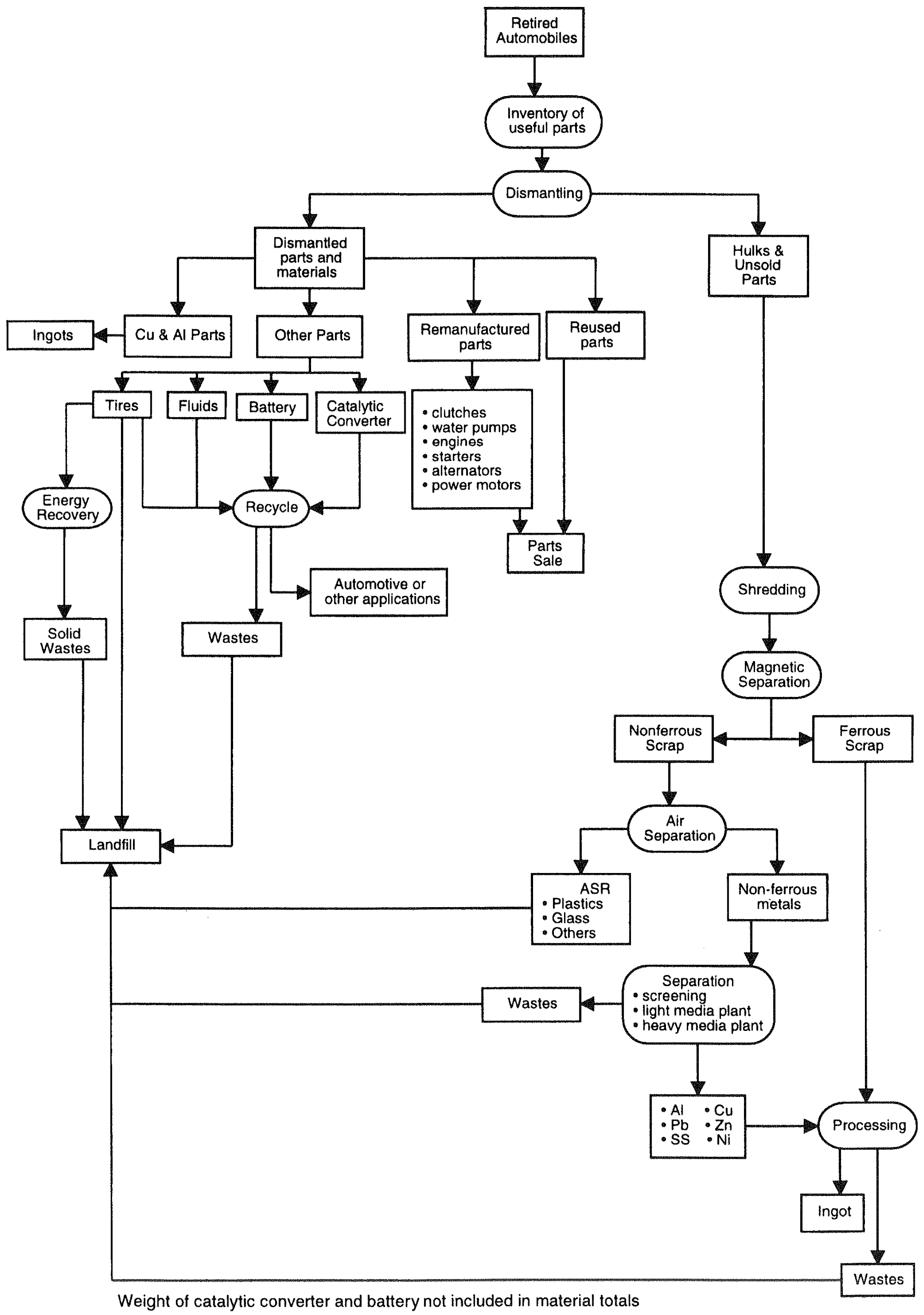
Year Ending June 30	Passenger Cars	Trucks and Buses	Total
1993	7,366	1,048	8,413
1992	11,194	1,587	12,781
1991	8,565	2,284	10,850
1990	8,897	2,177	11,073
1989	8,981	2,189	11,170
1988	8,754	2,251	11,005
1987	8,103	2,364	10,467
1986	8,442	2,309	10,752
1985	7,729	2,100	9,829
1984	6,675	1,601	8,277
1983	6,243	1,491	7,734

Source: Ref. 1.

6.1 Vehicle Retirement Process Description

The automobile is the most recycled product in the United States. Only 20% of glass, 30% of paper products, and 61% of aluminum cans are recycled[3]; however, approximately 94% of automobiles are recovered and recycled.[4] The remaining 6% currently are abandoned. In 1992, 11.2 million passenger cars were retired from use, based on the number of vehicles not re-registered.

A generalized flow diagram indicating retirement processes and materials streams is provided in Figure 6.1. As this figure shows, the main activities are dismantling, shredding, and postshredder material separation.



Weight of catalytic converter and battery not included in material totals

Fig. 6.1 The automobile retirement process. (Source: Refs. 1, 5, and 6.)

6.1.1 Dismantling

Retired automobiles are delivered to the dismantler or salvage yard by the owner or, more frequently, a towing service. A 1987 census counted 6,075 establishments reporting SIC code 5015 (vehicle wreckers/dismantlers) as their primary code.[7] Other sources cite 12,000 automotive dismantler operations in the United States.[2] These businesses provide a reliable source of used parts. A typical dismantler processes 400 to 500 cars per day.[3] The Automotive Recyclers Association, which is an industry trade association, currently has more than 2,000 members. This association refers to this stage of the life cycle as automotive recycling.

Two basic operations for processing retired vehicles are salvage yards that remove parts and retail/wholesale businesses that inventory dismantled parts. The type of automotive recycling and dismantling facility can be characterized by the age of the vehicles processed. Newer cars generally have a higher retirement value and therefore more parts must be sold to recover costs. Salvage yards (you-pull-it operations) tend to collect old cars.

At a retail/wholesale business, a full inventory of a car's usable parts is taken. Results of the inventory are entered into a computer and sent by satellite to a national databank, which allows other recycling centers to locate and purchase materials. Dismantlers remove materials and parts from retired vehicles primarily because of regulatory requirements and economic reasons. Current regulations ban hazardous materials and parts such as fluids and batteries from landfills. Thus, dismantlers drain radiator fluids, gasoline, engine oil, and refrigeration fluids from vehicles. Batteries also are removed because they can be economically recycled.

Fuel tanks are removed and drained because residual gasoline in tanks can cause a potential fire hazard during shredding of the hulk. Typically, empty tanks are then crushed and sent to the shredder for recycling. However, HDPE tanks pose a challenge to manufacturers and dismantlers for end-of-life management. Undamaged radiators are sold to the used-part market; leaky radiators remain with automobile hulks. Catalytic converters are removed because of their high economic value. Recovery of catalytic converters has increased from 12% prior to 1989[8] to 50 to 60% today, according to the U.S. Bureau of Mines' Internet homepage.

Parts with potential sale value either are reused directly or are remanufactured and subsequently reused. Clutches, water pumps, engines, starters, alternators, and motors for power windows typically are remanufactured. Virtually every other part that has potential sale value is collected for reuse. Value and demand for parts, legal requirements for part disposal, and available space in salvage yards are some of the factors influencing which parts are removed and sold by a dismantler.

Some dismantlers also separate aluminum and copper parts and sell material directly to nonferrous processors. Alternately, dismantlers can make ingots from copper and aluminum parts and sell them to the nonferrous scrap market. If parts removed for potential sale are not sold during a reasonable period of time, they are transported to the shredder as part-subsequent hulks. The time period for storing a part is a function of various factors such as the size of the dismantler, the model year of the vehicle to which the part belongs, and manufacturers' warranties.

What remains of the automobile after dismantlers remove all useful parts is commonly referred to as the hulk. Typically, hulks consist of steel structural materials, plastic dashboards, foam seats, and numerous other components. The hulk can be flattened for ease of transport or can be sent unflattened by the dismantler to the shredder.

Automotive dismantlers process approximately 10 million automobiles, buses, trucks, and motorcycles every year. These dismantlers supply 37% of all ferrous scrap to the nation's scrap industry.[1]

6.1.2 Shredding

Approximately 204 shredding operations exist in North America: 182 in the United States and 22 in Canada.[5] In addition to automobiles, shredders process white goods (appliances) and other waste objects containing sheet and light structural steel. Shredders are located primarily in heavily populated states, primarily east of the Mississippi River, where landfill space availability continues to decline. In Canada, most shredding operations are found in Ontario and Quebec, the country's most heavily populated provinces.

At shredder facilities, hulks are inspected prior to shredding to ensure that potentially hazardous components such as batteries, gas tanks, and fluids have been removed. Then the hulk is shredded into fist-sized pieces using large hammer mills. The ferrous fraction of shredded hulks is separated from the nonferrous components using magnetic separation.

Automobile shredder residue (ASR) consists of a light and heavy fraction. The light fraction, primarily containing nonmetals, is separated by air classification from the heavy fraction, consisting mainly of nonferrous metals. Then the ferrous and nonferrous components are transported separately to steel mills and nonferrous separators, respectively. The remaining light fraction of ASR, which comprises plastics, rubber, glass, dirt, and other low-density materials, is currently disposed in landfills. Because each separation step is not completely efficient, some contamination or loss of recoverable materials occurs. Separation of light ASR fraction from the heavy nonferrous-metallic ASR fraction can occur at the shredder or at the nonferrous separator facility. Some shredders make ingots from the nonferrous metals (i.e., aluminum and copper) and sell them to the scrap market. It should be recognized that ASR generally refers to the light fraction, which is currently disposed in landfills.

6.1.3 Separation and Metal Processing

Nonferrous Scrap/Heavy Fraction of ASR

The heavy fraction of ASR consists mainly of nonferrous metal scrap, some nonmetallic contamination, and entrained ferrous material. The nonferrous metals consist of aluminum, stainless steel, lead, copper, magnesium, zinc, brass, and nickel. ASR "reject" is separated from the nonferrous metals by gravity separation.

Aluminum and stainless steel are separated by light-media and heavy-media plants. Copper and brass require additional separation, which is accomplished by main sorting and image processing. Separated nonferrous scrap is sold as ingot to the nonferrous scrap market.

Ferrous Scrap

Ferrous scrap consists of iron and steel chunks. Approximately 70% of a typical passenger car is recoverable iron and steel. The scrap industry recycles approximately 10 million tons per year of shredded iron and steel, which is equivalent to the output of two average steel mills.[5] In addition to metal conservation, this results in considerable energy savings because four times as much energy is required to make steel from virgin iron ore as is needed to make the same steel from scrap.[5] The North American scrap industry has the capacity to process 14 million tons of iron and steel annually.

Steel made from scrap is chemically and metallurgically equivalent to steel made from virgin iron ore. More than half of all steel manufactured in North America is made of recycled material. Scrap acts as a coolant to control the temperature of various oxygen processes.

6.1.4 Landfill Disposal

Automotive material that is disposed in landfills during the end-of-life management stage currently includes most of the nonmetallic materials and a small fraction of entrained metallic materials. Typically, the light fraction of ASR can be separated at the shredder by air separation and can be sent directly to landfills from the shredder. Alternately, the shredder may perform only magnetic separation, and the light fraction of ASR then is separated at a nonferrous separator facility. The mass and composition of automobile shredder residue can be estimated by analyzing the material composition of a retired vehicle. The method is outlined in the next section.

Many of the nonmetallic materials currently are not economically recoverable because of low landfill disposal fees in the United States. As the plastics content of automobiles increases, the shredding industry will generate more solid waste, which may impact its economic viability.

6.2 Environmental Burden

Environmental burden in the retirement stage consists of wastes generated during different retirement processes and energy depletion resulting from these activities. The burden is strongly dependent on the material composition of vehicles and the infrastructure in place to process the vehicles. These factors also influence the potential for material and energy recovery, which reduces the burden both at retirement and upstream during subsequent materials production activities.

6.2.1 Resource Recovery and Waste

As indicated previously, approximately 6% of retired vehicles are abandoned,[4] often in rural areas which are too remote from dismantlers for economical transportation. The environmental impact related to these vehicles is uncertain, although many of the vehicles rust and fluids eventually leak into the environment.

Remanufacturing, reuse, and recycling represent important strategies for reducing environmental burden. The number of parts and components removed during dismantling and sold as reused parts is not available. The composition of the three major material fractions from vehicle recycling is indicated in Figure 6.2.

A simple model can be constructed to evaluate the theoretical potential for recycling an average retired automobile under current infrastructure conditions. Analysis will be based on a typical 1984 vehicle using material composition data from the American Metal Market.[1] A category designated "other materials" with a weight of 88 lbs is assumed to be nonmetallic. Table 6.2 organizes this material composition data into three categories for potential recovery: ferrous metals, nonferrous metals, and nonmetals.

Based on this composition, 77.9% of a retired automobile consists of metals. With a 95% recovery rate for metallics, 74% of automotive materials would be recovered for recycling. In addition to metals, other materials being recovered during end-of-life management include engine oil, coolant, some plastics, and 37% of tires. Assuming all lubricants are removed during dismantling and none of the other nonmetallic materials are recycled, the nonmetallic portion of ASR for a typical 1984 vehicle is 40% plastics, 26% rubber, 17% glass, and 17% other materials. By accounting for the current level of rubber recycling of 37%, the nonmetallic portion of ASR would have a composition of 44% plastics, 19% rubber, 18% glass, and 19% other materials.

TABLE 6.2. CATEGORIES OF MATERIAL USE IN 1984 VEHICLE

Material Category		Use, lbs	Percent of Total
Total Vehicle		3142	
Ferrous Metals			
	All Steel	1747	
	Iron	454	
	Total	**2201**	**70.1%**
Nonferrous Metals			
	Aluminum	137	
	Copper and Brass	44	
	Stainless Steel	29	
	Zinc	17	
	Powder Metals	19	
	Total	**246**	**7.8%**
Nonmetals			
	Plastics	207	
	Fluids, Lubricants	180	
	Rubber	133	
	Glass	87	
	Other	88	
	Total	**695**	**22.1%**

Under current recycling conditions, Oak Ridge National Laboratory estimates that ASR disposed in landfills will increase from approximately 2.2 million tons in 1992 to 2.5 million tons in the year 2000.[2] The Big Three U.S. automakers estimate ASR landfill disposition at 2.5 to

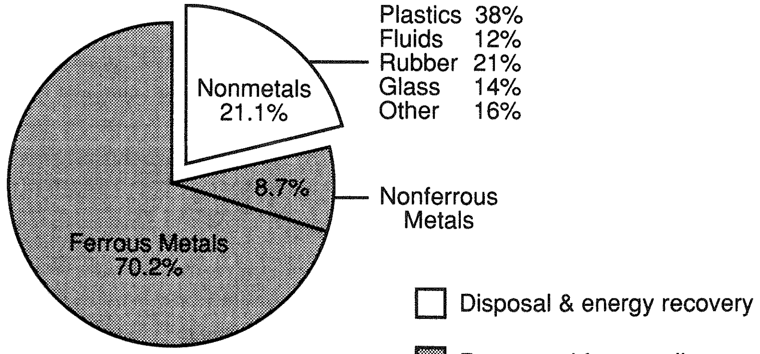


Fig. 6.2 Materials from recycled automobiles, 1994. (Source Ref. 1.)

3 million tons.[2] Using the Big Three figures, ASR currently accounts for 1.3 to 1.5% of municipal solid waste (MSW) in the United States. Although this may be a relatively small fraction of the total, it is important to recognize that MSW represents an aggregate of many different product and package types. Consequently, waste reduction will require efforts directed at each of these different fractions. From a societal perspective, it may be more efficient to allocate resources to the larger fractions of MSW which include paper and yard waste.

In most states, ASR is designated as nonhazardous waste, and it is disposed in RCRA Subtitle D landfills. In California, ASR does not meet cadmium restrictions; therefore, a chemical fixation is required which adds $20 per ton to the tipping fee. Other states require treatment of ASR to immobilize heavy metals or have imposed other regulations on ASR disposal.

6.2.2 Energy

The amount of energy consumed in end-of-life management processes is relatively small in comparison to other life cycle stages. Energy for different retirement processes is indicated below.

Dismantling

Dismantlers use a variety of tools such as air-driven tools, impact notches, hand tools, abrasive blades, and oxyacetylene torches to remove the parts. Oxyacetylene torches are used only when parts cannot otherwise be removed. Most of the dismantling requires human energy. Mechanical energy for dismantling is relatively small and is excluded from this study. Dismantlers send all hulks, unsold metal, and nonmetal parts to the shredder.

Shredding

Shredding energy varies as a function of load (tons/hr) and the horsepower requirements of the shredder motor (from 2000 to 7000 hp). The following is an estimate of shredder energy as obtained from Texas Shredder:

- Shredder energy = 2827.12 Btu/s
- Operating load = 67.36 lb/s

Thus, shredder energy equals 42 Btu/lb or 97 kJ/kg. Shredder energy quoted by Sullivan[9] is approximately 51.19 Btu/lb; the U.S. Department of Energy estimates approximately 32 Btu/lb.

Shredding machines are powered by electricity. Process waste from the shredder is minimal. The shredder sends all its ferrous and nonferrous scrap to steel mills and nonferrous separators. Shredding energy includes shredding and magnetic separation of ferrous materials.

Nonferrous Separation

Nonferrous separation energy varies, depending on the types of materials separated. First, ASR is separated in a light-media plant. According to Huron Valley Steel, typical energy requirements for a light-media plant are 66 kJ/kg, whereas separation in a heavy-media plant usually requires 170 kJ/kg.

Transportation

Transportation is required between different retirement processes. For example, hulks are transported from dismantlers to shredders, and shredder materials then are transported to ferrous and nonferrous processors. ASR is transported from nonferrous processors to landfills. Separated nonferrous metals are transported from nonferrous processors to the nonferrous metal industry. The typical transportation energy for a diesel-operated tractor-trailer is taken from Ref. 10 as 1945 Btu/ton-mile or 2.05 MJ/ton-mile. Average transportation distances are as follow[11]:

- Dismantlers to shredders = 100 miles
- Shredder to metal processors = 200 miles
- ASR to landfill = 200 miles

This results in a transportation energy requirement of 678 kJ/kg per retired automobile.

Table 6.3 shows the approximate energy demands from different processes for both U.S. and German scenarios. Transportation constitutes the major energy burden in the retirement stage. Transportation is diesel operated, whereas shredders and separators are operated by electricity.

TABLE 6.3. ENERGY REQUIREMENTS FOR AUTOMOBILE RETIREMENT

Retirement Processes	Energy Use U.S. Estimate (kJ/kg)	Energy Use Germany (kJ/kg)
Dismantling	-	-
Shredding	97	185
Separation	26	64
Transportation	678	360
Total	801	609

Source for German condition: Ref. 12.

6.3 Design and Management Opportunities for Improvement

Table 6.4 provides options and issues related to each of the major constituents in automotive shredder residue. Vehicle recyclability is receiving increasing attention.[13–15] Some of these issues are elaborated further in the following sections.

Residual fluids from vehicles are a major problem facing dismantlers. Fluids not drained from engines, transmissions, fuel lines, and other parts are potential sources of contamination in shredding and subsequent separations.

6.3.1 Plastics Recycling

Recycling and disposition of automotive plastics raise complex issues. To be successful, plastics recycling requires viable markets and uses for recovered parts and materials, infrastructure and sites for parts disassembly, and reduced labor costs for disassembly.[16] Currently, most plastics from retired automobiles are disposed in landfills, although battery housings and some old bumpers are recovered for automotive and other applications.[17]

TABLE 6.4. OPTIONS AND ISSUES IN MANAGING AUTOMOTIVE SHREDDER RESIDUE

Constituent	Percent of Total	Options	Issues
Polymers	34%	• Recycle - Thermoplastics returned to same application - Thermosets ground, returned in small percentage of compression molded - Textile polymers into injection molding - Seat foam into rebond foam • Energy Recovery: high fuel value • Pyrolysis: recover gas, oil, fillers	• Recycle: cost of collection and processing greater than material value • Energy Recovery/Pyrolysis: not economical, some technical issues, social barriers
Fluids	17%	• Recycle • Rejuvenate and reuse fluids • Energy Recovery: high fuel value for some fluids	• Recycle and Rejuvenate: improved, faster methods needed • Energy Recovery: economics, emissions, social barriers
Glass	16%	• Recycle - Clean glass (side windows): may recycle for nonappearance parts - Contaminated glass (windshield, rear window, mirrors): may recycle into reflective road paint and concrete	• Disassembly is difficult due to adhesive bonding of windshields, rear windows, and encapsulated windows • Contamination with bonded-on items and encapsulation
Rubber	12%	• Recycle - Thermoset rubber as filler - Thermoplastic rubber returned to same or less demanding application • Energy Recovery: high fuel value • Pyrolysis: recover gas, oil, metal	• Recycle: cost of collection and processing greater than material value; improvement needed • Energy Recovery/Pyrolysis: not economical, some technical issues, social barriers

Courtesy of Roger Heimbuch and Wendy Lange, General Motors Corporation.

Plastics recycling depends on recovery of plastic parts at the dismantling yard and subsequent processing at molder sites into new products. For recyclers, plastics are a problem because cars contain approximately 25 chemically incompatible kinds of plastics which cannot be melted together and reused. For example, a study conducted by the Vehicle Recycling Partnership (VRP), which is managed by the U.S. Council for Automotive Research (USCAR), indicated that automotive instrument panels are made of as many as 15 types of plastics.[3] Figure 6.3 shows the percentage composition of plastics in the automobile.

Automobile manufacturers are considering a reduction in the number of different plastic resins used in vehicles to increase the overall viability of plastics recycling.[2] Certain types of plastics are more difficult to recycle than others. For example, thermosets cannot be melted. Thermosets either can be ground into a fine powder and used as a filler with virgin resins, or they can be burned to retrieve their heat energy. However, the economic viability of these approaches to recycling is suspect at this time. The other class of plastics, thermoplastics, can be melted and reformed into new products. Fortunately, most plastics (76%) in automobiles are thermoplastics.[18] Listed below are some of the research work and initiatives in progress for plastics recycling.

wTe Corporation's Multiproducts Recycling Facility (MPRF), Boston, MA	MPRF was established in 1993 to generate clean plastic streams from plastic items contaminated with foreign materials. It includes an upgraded sink/float classification system, state-of-the-art rotary grinder, and a shear shredder.[19]
Advanced Plastics Recycling	The American Plastics Council (APC) and MBA Polymers, Inc., have opened a facility in Berkeley, CA, which focuses on identification and development of new mechanical recycling technologies for plastics.[19] The line includes a size reduction operation, which can accommodate foreign materials such as metals, a three-stage air classification system that can produce up to four different streams using only air, and a low-energy, high-throughput wet grinding system. After proper sizing, the materials pass through a series of hydroclone separation systems that remove remaining foreign materials and sort plastics by density—a process said to be much faster than commonly used sink/float methods. The line also includes a new paint and coating removal system using high temperature and high pressure in a water-based process that rapidly breaks down paint and coatings on flakes of plastics. The pilot facility is intended to serve as a future full-scale recycling system—technology that will ultimately be transferable to many industries and recycling operations.
Plastics Identification	Bruker Instruments, Inc., developed a semiportable instrument called P/ID 28 in cooperation with APC, which can identify 23 different types of plastics within five seconds.[19] The instrument uses reflected light to scan the parts. The system requires minimal sample preparation and will be evaluated by the VRP program managed by USCAR.
Dismantling	The APC is involved in dismantling automotive plastic parts. Plastics are sorted by resin type and sent to wTe Corporation's MPRF facility for processing. It was learned that new cars require significantly less labor than old cars to recover plastics, and that almost 40% of the parts recovered from new cars had some sort of resin identification.[19]
ASR Application Development	Current research performed by the Department of Civil and Environmental Engineering at Michigan State University with support from APC has found that ASR has practical and environmental use in concrete construction.[19] The study determined that ASR particles, when added to concrete at 2 to 3% by volume, increase its tensile strength, crack resistance, and impact resistance without significantly altering other desirable properties of concrete such as durability and environmental safety. If concrete with 3% ASR by volume captures 20% of the existing market, more than 91,000 tons/year of ASR can be consumed.
DuPont Automotive's Nylon Recycling	DuPont Automotive is researching the commercialization of a proprietary process called "ammonolysis" for depolymerizing nylon products such as mixed PA66 and PA6 for first-quality uses. In the process, 98% pure nylon melt is pumped into an ammonolysis reactor and depolymerized at 330°C and 7 MPa using a phosphate catalyst. The reaction mix is distilled to recover ammonia and remove carbamate. The output of the process is hexamethylenediamine (HMD), which is the base chemical for manufacturing PA66 nylon resin.
GE Plastics Bumper Recycling	GE Plastics and Ford Motor Company have initiated a program to recycle, from scrap yards, Ford bumpers made from GE Plastics' XENOY resin.[20] The recent buy-back program establishes a fair market price for a whole, recovered bumper based on factors such as costs for removal, handling, and storage; increased car value due to lower ASR from hulks; the value of bumpers as a material feedstock; and profit for the dismantler. After the dismantler has accumulated enough bumpers to make shipping economical, the bumpers are sent to a central processor. After a bumper is identified as being made of XENOY resin, all secondary-operation contaminants are removed including decorative rub strips, license plate brackets, fog lamps, bumper stickers, adhesives, and paint. Most are removed manually; adhesives and paint are removed by a water-based process. Initially, recycled XENOY will be targeted at high-heat ABS applications. Eventually recycling technology will advance to allow the use of recycled material in the original application. Ford Motor Company now uses material from salvaged plastic bumpers to mold new tail-lamp housings for Ford Taurus and Mercury Sable wagons.[17]
Ashland Chemical's Composite Recycling	Ashland Chemical has developed a proprietary recycling process known as "Cured Unsaturated Polyesters Glycolysis for Recycle Reactant," which recovers and recycles organic components from thermoset polyester composites into new thermosetting resins. The process uses heated glycols to break down thermoset polyester composite scrap into new reactant raw materials. The resulting polyols can be used to make unsaturated polyester resins, which have been used for press molding and automotive SMC applications in the company's laboratories.
SMC Recycling	Currently, the best SMC recycling approach is to regrind filler and fiber fractions for use in new products.[18,21] Phoenix Fiberglass is believed to be the only North American company commercially recycling SMC composites. Eagle-Picher Automotive produced the first exterior part made of recycled SMC—a spoiler for Chrysler's Dodge and Plymouth Neon. Currently, most SMC recycling is performed by mechanical separation and attrition. However, chemical recycling such as pyrolysis also can be used, particularly in cases in which SMC is highly contaminated with other materials.
Energy Recovery for RIM	Researchers from Mobay and Dow Chemical have evaluated different energy recovery methods for RIM polyurethane scrap material.[22] Three separate technologies—fluidized bed, mass burn, and rotary kiln—were examined, and the resulting stack gases were analyzed for conventional emission components. The energy content of RIM ranges from 28 to 32 MJ/kg, depending on filler content. This compares favorably to 32.2 MJ/kg energy content of coal. RIM combustion results in lower particulates, NO_x, and SO_2 emissions than coal or fuel oils, and lower CO_2 emissions than typical fossil fuels.
Pyrolysis of SMC	Pyrolysis is the controlled thermal decomposition of an organic material into one or more recoverable substances through the application of heat in an

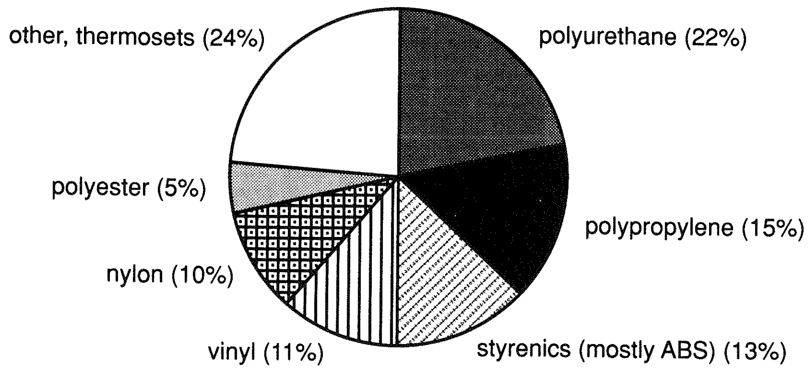


Fig. 6.3 Plastics used in automobiles. (Source: Ref. 18.)

Pyrolysis of SMC *(continued)*	oxygen-free environment. Pyrolysis decomposes plastics and rubber into chemical products that can be reused, while preserving their energy content.[18] The major advantage of pyrolysis is that it is well suited for handling plastics contaminated by paint and adhesives. Although pyrolysis is a promising recovery technique for automotive plastics, it is not yet economically feasible.[16] The major barrier in pyrolysis is that the chemical composition of ASR is too complex for existing technology. Therefore, plastics must be separated from ASR before chemical processing.

6.3.2 Tire Recycling and Recovery

In addition to plastics, tires represent another unique challenge for vehicle retirement. Tires consist of rubber, steel, and textiles. Approximately 264 million tires are manufactured annually in the United States for highway and off-road vehicles.

Figure 6.1 shows the relative occurrence of different disposition pathways for the 242.5 million tires disposed in 1990. Approximately 63% of worn-out tires are disposed in landfills, stockpiled, or illegally dumped. In addition to land disposal, approximately 33% are used as an energy source in cement kilns, pulp and paper mills, and dedicated energy facilities. The remaining 4% are recycled.[6]

Retreading can extend the useful life of a tire by applying a new tread to a worn tire that has a good casing. The use of retreads is on the decline. During their peak 20 years ago, 35 million retreads were used on passenger cars and light-duty trucks, whereas today an estimated 13 million retreads are used.[23] The EPA estimates that 20 million fewer replacement tires would be needed annually if all suitable passenger cars and light-duty trucks were retreaded.[24]

Tires can be burned whole, shredded or chipped, or processed into tire-derived fuel. Combustion of tires yields 14,000 to 16,000 Btu/lb, compared to 12,000 to 14,000 Btu/lb for coal. One million tires can replace 12,170 tons of coal[25] while producing only 57.2% of the ash content of coal.

At the end of its service life, the average 25-lb passenger tire will have lost approximately 5 lbs of rubber as a result of normal tread wear.[26] Approximately 700,000 tons of rubber are dissipated on U.S. roads annually.

6.3.3 Mercury Switch Substitution

Automotive applications of mercury or mercury compounds that have been confirmed in current North American vehicles include light switches, antilock braking systems, active ride control (ride-leveling sensors), high-intensity discharge systems (headlights, tail lamps), and virtual image instrument panels.[27] Because as many as 25,000 parts compose a typical automobile, all mercury sources probably have not been identified. Table 6.5 describes known current and past applications of mercury in automobiles.

TABLE 6.5. MERCURY USE IN AUTOMOBILES AND ALTERNATIVES

Mercury-Containing Products	Quantity	Uses	Available Alternatives
Antilock Brake Systems (ABS)	Approximately 3,000 mg	Some four-wheel drive vehicles, other ABS use unknown	
Headlamps	0.5–1 mg	High-intensity discharge (HID) lamps	Standard halogen or tungsten filament for car headlights
Radios	NEA	Rechargeable batteries	Mercury-free versions
Remote Transmitters	NEA	Mercury oxide batteries	Zinc air, other mercury free
Light Switches	1000 mg	Activates convenience lights in trunk, underhood	Various electromechanical switches
Ride Control	Approximately 1000 mg		
Speedometers	<40 mg		

NEA - No estimates available.
Source: Ref. 28.

Mercury use in automobiles is believed to be concentrated in the three areas shown in Table 6.6. Of the confirmed North American applications of mercury, switches used in lighting, antilock brake systems, and active ride control accounted for 99.9% of the total mercury used.[27] An estimated 9.8 metric tons of mercury are used for automobile switches annually. However, Nachtman and Hill[27] report that an average switch weighs approximately 0.8 g and that 14 million switches are sold to the automotive industry annually. This would result in slightly more than 11 metric tons used annually by the automotive industry.

TABLE 6.6. MOST SIGNIFICANT MERCURY USES IN AUTOMOBILES

Component or System	Mercury Use (metric tons)	Percent of Total
Electric Switches	8.53	87%
Antilock Brake Systems	1.18	12%
Active Ride Control	0.10	1%

Source: Ref. 27.

Chrysler, Ford, and General Motors have pledged to identify reasonable alternatives to mercury switches and to introduce mercury-free switches as soon as possible. In addition, the Society of Automotive Engineers is preparing a white paper on mercury that emphasizes the need to find feasible substitutes for present mercury applications during design. However, in some cases no feasible substitute may exist.

6.3.4 Design for Recyclability

Henstock[29] provided an excellent although now somewhat outdated overview of design for recyclability and specifically addressed the automobile. Strategies identified to facilitate recovery by avoiding material contamination are shown in the following list.

Changes in Design	• Mechanical disassembly may be simplified • An effort may be found to avoid self-contaminating combinations of materials
Changes in Materials	• Materials may be standardized • Materials may be identifiable • Harmless materials may replace deleterious ones
Changes in Reclamation Techniques	

A comprehensive review of vehicle recycling initiatives in Europe is provided by Curlee *et al.*[2] Activities of European automakers include a pilot car recycling plant near Lyon, which is a joint venture among Peugeot SA Group, Compagnie Francaise des Ferrailles (a scrap recycler), and Vicat (a cement-maker). This $4-million, two-year venture, launched in June 1991, claims a 95% recycling rate.

6.4 Government and Industry Initiatives

6.4.1 Vehicle Recycling Partnership—USCAR

The Vehicle Recycling Partnership (VRP) was established in November 1991 "to identify and pursue opportunities for joint research and development efforts pertaining to recycling, reuse, and disposal of motor vehicles and vehicle components. The partnership also will promote the increased use of recyclable and recycled materials in motor vehicle design." Major goals of the program are as follow: 1) to reduce the total environmental impact of vehicle disposal, 2) to increase the efficiency of disassembly processes to enhance recyclability, 3) to develop material selection and design guidelines, and 4) to promote socially responsible and economically achievable solutions to vehicle disposal.

The current Vehicle Recycling Development Center (VRDC) Engineering Projects of the VRP are as follow:

- Fluid Removal and Recycling
- Seat/Foam Recycling
- Data Analysis and Collection (to provide dismantling sequence information, time studies for collection, recovery rates and volumes, and assessment of difficulty)
- Resin Identification and Sorting
- Glass Recycling
- Bumper/Fascia Recycling
- Interior Trim Recycling
- Instrument Panel Recycling
- Elastomer Recycling

- Textile Recycling
- Collection and Recycling (to evaluate procedures, provide material identification information, enhance infrastructure, and determine geographic, transportation, and economic issues influencing collection)
- AAMA Initiatives (to provide workable recyclability calculations and categories and to clarify protocols)
- Recyclability Demonstration (to provide consistent technical determination of recyclability and to illustrate alternative design concepts)
- Automotive Shredder Residue Initiatives
- Argonne Cooperative Research and Development Agreement (CRADA) (to support and leverage research on automotive recycling without duplication)
- VRDC Library—Information Retrieval on Recycling
- VRP Research Support (with the University of Detroit-Mercy)
- Economics Model (to provide economic selection criteria for future designs and recycling techniques)
- Design for Disassembly
- Adhesive Recycling: Selection and Compatibility

6.4.2 Economics

The economics of the retirement process depend on the value of old vehicles and their materials, processing costs, scrap value, and landfill disposal costs.

Value of Old Vehicles

Retired vehicles are valued based on their parts and materials. This value can be increased by two approaches: 1) increasing the value of materials and parts, and 2) using materials in the vehicle that can be easily recycled, thus increasing the profitability of recycling by reducing processing costs.[15] The second approach places responsibility for establishing and maintaining retired vehicle value on OEMs, suppliers, and users.

Dismantlers in the United States currently pay final owners for retired vehicles. The procurement costs for retired vehicles include payments to final owners and the cost of towing nonfunctional vehicles to the salvage yard. A recent survey within the Ann Arbor area indicates a typical towing charge of $30. The dismantler usually tows the vehicle. This survey indicates that payment to the last user can vary from $25 to $50, depending on the type of vehicle. If the vehicle owner delivers the vehicle directly to the dismantling yard, payment may vary from $50 to $80.

As the plastics content in the automobile increases, automobile shredder firms are becoming more concerned about the economic viability of their operations. A simplified analysis by Field and Clark[15] indicated that the scrap value of hulks decreased from $60.57 for 1976 automobiles to $51.51 for 1989 automobiles as the recyclables fraction decreased and nonrecyclable materials use increased. The value of steel and nonferrous scrap and the costs for shredder residue disposal, transportation, and processing were evaluated to estimate the value of hulks. Current value for a hulk can vary from $30 to $60.

In Europe, retired vehicles have a negative value because the cost of ASR disposal exceeds the salvage value of recyclable materials. In Germany, where mandates drive the country's recycling industry, consumers pay $25 to $150 to retire their vehicles.[30] ASR is designated as a hazardous waste in Germany, which results in higher disposal costs there compared to those in the United States.

Processing Costs of End-of-Life Automotive Stakeholders

End-of-life stakeholders include dismantlers, shredders, and nonferrous processors.

Dismantlers

Dismantler costs include transportation and processing. On average, transportation from dismantlers to shredders for flattened and unflattened hulks costs $0.12 and $0.18/ton-mile, respectively.[11] Assuming a 50% split between flattened and unflattened hulks, total transportation cost is $0.15/ton-mile. Assuming an average transportation distance of 100 miles between dismantler and shredder, the average transportation cost from dismantler to shredder is $0.0165/kg. For an average hulk weight of 2300 lb (or 1042 kg), this results in a total transportation cost of $17.19.

An APC case study indicates that the total fixed and variable cost for dismantlers is $145.58/hulk and total credit to dismantlers is $215.54/hulk.[11] This represents a gross profit margin of $69.96/hulk and simple payback within 2.86 years. The APC study was based on 1992 dollars and made the following key assumptions[11]:

- Dismantler income from converters, batteries, tires, and fluids is $170.00.
- The hulk sales value to the shredder is $30.00.
- The acquisition cost to the dismantler for an old automobile is $30.00.

Shredders

The APC case study indicates that the total fixed and variable cost for shredding is $116.64/hulk, and total credit to dismantlers is $125.21/hulk.[11] This represents a gross profit margin of $8.57/hulk and simple payback within 17.5 years. Thus, the average dismantler and shredder have positive gross profit margins. However, shredders have a lower profit margin compared to dismantlers. Although the cost of shredding is lower than dismantling, the sale value of shredder materials also is lower than material recovered by dismantlers. Shredder costs include transportation to metal processors. For an average distance of 200 miles between shredders and metal processors, this cost is estimated at $34.38 per vehicle. Shredder income depends on the sale of ferrous materials (approximately 71% of the vehicle) to steel mills. Thus, the factors influencing shredder profits are the following:

- Higher metal content in automobiles
- Proximity of shredders to scrap metal industries
- Production of clean ferrous and nonferrous scrap from automobile hulk

Nonferrous Processors

Information on the economics of nonferrous processing was not discovered. Costs to nonferrous processors typically include transportation and processing. The scrap value of recovered metals dictates processor credits. Copper (approximately $1.98/kg), brass ($1.35/kg), aluminum (approximately $0.91/ kg), and stainless steel ($0.76/kg) usually have the highest scrap value.

Landfill Disposal Cost

Landfill disposal cost is a function of various factors, as indicated below[15]:

Environmental	• Depletion of available landfill space
Cost	• Processing and land cost
Legal	• Difficulty in siting landfills, including expensive permitting and litigation process • Government regulation and policies

In the United States, ASR is designated as nonhazardous waste and is disposed in RCRA Subtitle D landfills. The National Solid Waste Management Association estimates that the national average landfill tipping fee is $30.25 per ton. Landfill tipping fees vary across regions. Many successful waste reduction and recycling initiatives by industry and municipalities have extended the life of current landfills. This in part accounts for the relatively low cost of solid waste landfill disposal. One landfill facility used for ASR disposition in Southeastern Michigan has a tipping fee of only $9/ton.[31] In California, ASR does not meet cadmium restrictions; therefore, a chemical fixation is required which adds a cost of $20 per ton to the tipping fee. Other states require treatment of ASR to fix and immobilize heavy metals or have imposed other regulations on ASR disposal.

Assuming $30.25 per ton for landfill disposal cost, the total cost for disposing 25% by weight of a 1984 vehicle (695 lbs or 315 kg) is $10.51 per vehicle. Table 6.7 indicates the costs and credits for recovered parts and materials to several different stakeholders in end-of-life management.

TABLE 6.7. RETIREMENT VALUE AND COSTS FOR A 1984 AUTOMOBILE

Stakeholder	$/Vehicle
Dismantler	
Fixed + Variable Cost	(145.58)
Credit	215.54
Shredder	
Fixed + Variable Cost	(116.64)
Credit	125.21
Nonferrous Processor	
Scrap Value	101.00

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Chapter 7

Systems Analysis of the Total Life Cycle

Previous chapters addressed discrete stages of the life cycle, beginning with materials production and concluding with retirement. This chapter examines the total life cycle of the automobile as a system. A simplified process flow diagram of the vehicle life cycle was provided in Chapter 2 as Figure 2.2. Where possible, environmental burdens are aggregated. In addition, the distribution of burdens and impacts among stages will be analyzed.

Although the chapters of this book are organized into discrete vehicle life cycle stages, it is essential to also evaluate the interconnections among the stages that define the automobile life cycle system. The product material (e.g., steel, aluminum, plastics, rubber, and glass) is transformed across each stage by a process component at that stage. The product material entering the next stage has inherent characteristics that influence the behavior of the product component at that phase. The process component at that stage can be viewed as an independent system that may process other products and has a unique set of requirements that influences its behavior. The process activities and principal components for the automobile life cycle in consecutive order are: mining (mining equipment), drilling, materials processing (steel mills and chemical plants), parts fabrication (molding and stamping equipment and facilities), assembly (equipment and assembly plant), use (vehicles and the infrastructure that includes roads and gas stations), service (body shops and repair shops), dismantling (salvage yards and wholesale/retail dismantling operations), shredding (shredder), nonferrous separation and recovery (nonferrous processor), and management of residual materials (landfill and incineration with energy recovery).

Opportunities to improve the automobile exist at each stage of its life cycle. Process improvements for a given stage can be made independently without affecting other stages. Alternately, product design changes can be made which may be integrated with process design changes at one or more stages of the life cycle.

Key stakeholders who are responsible for the management of the automobile life cycle are material suppliers, parts fabricators, OEMs, customers, service and repair professionals, dismantlers, shredders, nonferrous processors, waste managers, regulators, insurers, and investors.

7.1 Environmental Burden

7.1.1 Resource Use

An accurate summary of product, process, and distribution material inputs for the total life cycle is not available. In Chapter 3, Table 3.1 presented the material composition of a typical vehicle; Table 3.2 estimated total product materials consumed by the automotive industry. However, the total impact of process materials for each stage of the life cycle is much more difficult to determine.

7.1.2 Energy

Several investigators have conducted life cycle energy analyses of the automobile and automotive parts and components. The results of these studies are summarized in Table 7.1.

TABLE 7.1. LIFE CYCLE ENERGY USE FOR VARIOUS AUTOMOBILES

Data Source and Automobile Type	Energy Use, GJ Production	Use	Service	End-of-Life	Total	Use and Service (%)
Ref. 1, Average C Class[a]	83	503	62	-18	630	90
Ref. 2, 650 kg[b]	33	318			351	91
2000 kg	135	1515			1650	92
Ref. 3, Average	44	540		584	92	
Ref. 4, 1395 kg[c]	81	788	16	1.5	886	91
1157 kg	67	646	13	1	727	91
Electric Vehicle (EV) 1385 kg	123	384	43	1.5	552	77

All internal combustion engines, except as noted.

[a] The use phase consists of fuel consumption (390 GJ), fuel supply (68 GJ), maintenance (62 GJ), and infrastructure (45 GJ).

[b] 120,000 km for 650-kg car, 200,000 km for 2000-kg car.

[c] 120,000 miles for all vehicles. 1395-kg automobile, 24.3 mpg; 1157-kg automobile (functional equivalent of EV), 29.6 mpg; EV 3.55 mi/kWh, equipped with sodium sulfur batteries.

Clearly, the use phase of the life cycle dominates in primary energy consumption relative to other stages of the life cycle. The four studies cited in Table 7.1[1–4] consistently demonstrate that the use phase consumes approximately 90% of total life cycle energy for an internal combustion engine vehicle (ICEV). Some of these studies address only production and operation energies; others also include energy consumed for maintenance, infrastructure, and retirement.

Sullivan and Hu[4] determined that the use phase contribution for an EV is considerably less than for an ICEV. They estimated that approximately 77% of total life cycle energy for an EV occurs in the use phase.

In all these studies, it is not evident whether energy required for the production of process materials for the manufacturing stage was included. Neglecting this energy significantly understates the total energy for production of the automobile and thus exaggerates dominance of the use phase.

7.1.3 Emissions

Greenhouse gas emissions from a light-duty ICEV using reformulated gasoline were estimated at 491.2 g/mi CO_2 equivalents (333.7 g/mi for vehicle use, 101.6 g/mi for fuel production, 14.0 g/mi for car assembly, and 41.9 g/mi for materials production).[5]

A study by Schuckert *et al.*[2] of life cycle primary pollutants shows that CO emissions are concentrated in the use phase, but other pollutant emissions such as methane, NO_x, and SO_2 are more evenly distributed among manufacturing, use, and fuel production activities. Figure 7.1 shows cumulative emissions for small- and upper-class vehicles. For methane (CH_4), manufacturing accounts for approximately 40% of total life cycle emissions. Emissions for this study were much lower than those reported by Ross *et al.*[6] for actual operating conditions.

DeLuchi[5] analyzed the greenhouse gas emissions for different energy sources for ICEVs and EVs. These data are presented in Table 7.2.

7.2 Public Policy and Legislation

Government can play an important role in promoting life cycle design and assessment through regulatory and voluntary programs. The current regulatory framework in the United States was not developed to minimize life cycle environmental burdens and impacts. For example, EPA has not yet considered the distribution of air pollutant emissions between manufacturing and use for vehicles. The relative contribution of air pollutant emissions, as shown in Figure 7.1, was not used to set the Clean Air Act standards in 1990.

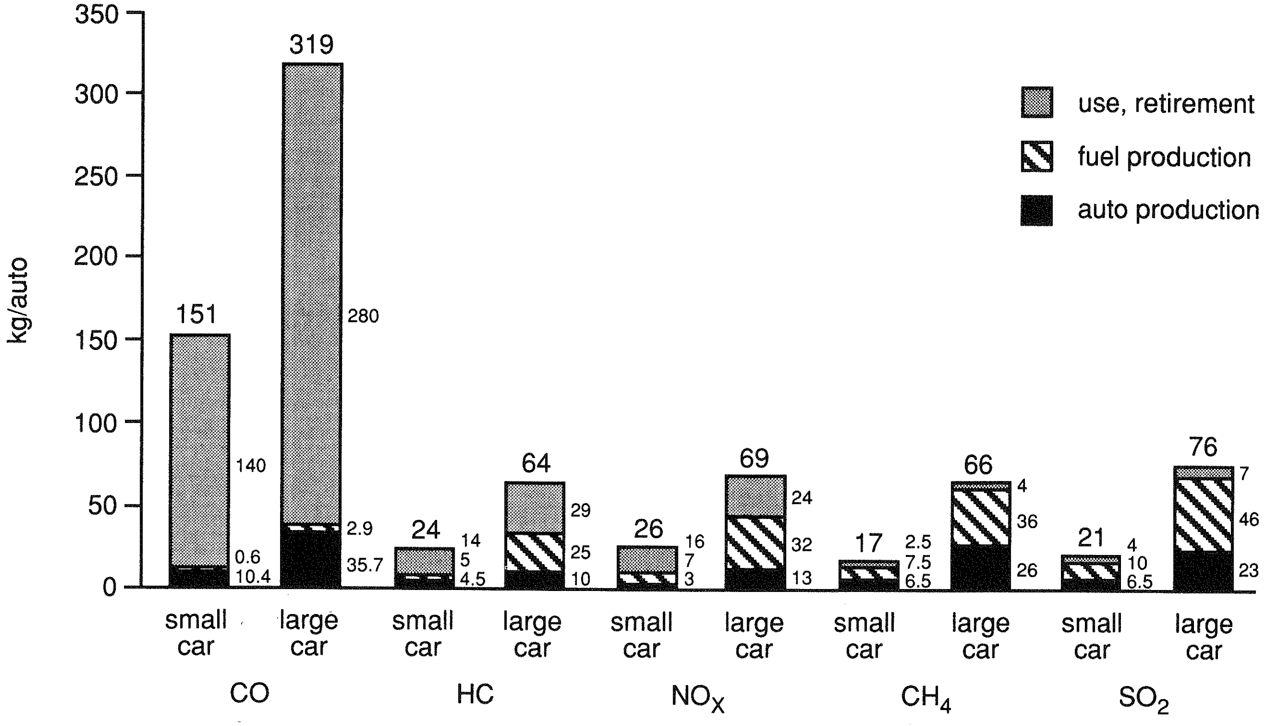

Fig. 7.1 Life cycle emissions for small- and upper-class vehicles. (Source: Ref. 2.)

TABLE 7.2. LIFE CYCLE CO_2-EQUIVALENT EMISSIONS FOR ICEVs AND EVs, GRAMS PER MILE

Stage or Activity	EV, National Grid	ICEV, Reformulated Gas
Vehicle Use	0.0	333.7
Fuel Production	445.6	101.6
Automobile Assembly	14.4	14.0
Material Production	46.6	41.9
Total	506.6	491.2

Source: Ref. 5.

One exception to the general lack of consideration for product life cycle issues in federal regulations is the Toxic Substances Control Act (TSCA). TSCA regulates the manufacture, processing, distribution, use, and disposal of chemical substances to ensure that new chemicals do not pose unnecessary risks to human health or the environment. Discrete stages of the life cycle of a chemical are addressed, but evaluation of life cycle aggregate burdens and impacts does not appear to be part of the risk assessment process for new chemicals.

The media-specific regulatory framework formerly practiced by EPA was effective in driving environmental impact reduction. However, the Agency's recent pollution prevention strategy[7] improves on past practice by adopting a multimedia approach to environmental protection, which acknowledges the importance of the life cycle framework. The EPA is now struggling with how to address multimedia pollutant regulation. Developing policies and a regulatory framework to encourage and support improvements in a product life cycle is equally challenging.

The EPA regulations address several different system boundaries and jurisdictions, ranging from protecting individual consumer and occupational health to ensuring regional air quality and controlling emissions from individual facilities. Consequently, revising the regulatory framework to promote improvements for a product life cycle would be a major challenge given the existing complex web of regulations. Pilot projects such as the Common Sense Initiative will serve as an important opportunity to test new approaches that emphasize systems analysis.

The U.S. Congress Office of Technology Assessment (OTA) recently conducted a thorough study of policy options for promoting green product design.[8] Although existing market incentives and environmental regulations have been somewhat effective in promoting sustainable practices, OTA concluded that Congress can foster further progress in this area by supporting research, information for consumers, policies that internalize environmental costs, and coordinating and harmonizing various programs. Table 7.3 outlines regulatory and market-based incentives to internalize environmental costs associated with a product system.

Policy mechanisms to support the commercialization of ultra-efficient vehicles were analyzed recently by DeCicco and deLaski.[9] Ultra-efficient vehicles refers to vehicles "having fuel efficiencies substantially higher than current mass-market vehicles while maintaining contemporary standards for size, affordability, range, performance, and other vehicle amenities." DeCicco and deLaski organized market transformation tools into two categories: 1) technology push, which includes research, technology development, demonstration, and manufacturer incentives, and economic development programs and 2) technology pull, which includes performance standards, sales mandates, strategic procurement, voluntary commitments, consumer incentives, and marketing and consumer information. They advocate a comprehensive strategy that would involve most of the technology push and technology pull elements.

The government also has a major responsibility in supporting research to develop and coordinate the environmental databases necessary for life cycle assessment. The lack of environmental data is currently a major limitation for decision-makers in product development. In addition, corporations that must already meet a variety of government reporting requirements could modify and expand their information gathering to serve both internal decision-making needs and the needs of outside stakeholders. With such an expanded system, perhaps encouraged by government support, an environmental profile (energy use, resource inputs, and wastes produced) of product systems at each life cycle stage would be publicly available. However, proprietary information would have to be protected. In the U.S. Congress, Representative Brown of California recently proposed the Environmental Technologies Act (H.R. 3603) for funding to support further research in life cycle assessment, but this proposal was defeated.

7.3 Design Initiatives and Management Opportunities

Systems analysis based on the automobile life cycle is useful for both incremental improvements in automotive design and more radical improvements associated with leapfrog technology.

The automotive industry is beginning to apply life cycle assessment and other life cycle design tools, as evidenced by numerous case studies and demonstration projects.[10] However, these approaches to integrating environmental considerations into product development remain in their infancy. Tools for guiding environmental improvements, such as guidelines and checklists, have been more widely implemented than analysis tools such as life cycle assessment. For example, guidelines and checklists are being developed to facilitate material selection and vehicle recycling.

7.3.1 Material Selection

Material selection is an activity that directly affects the life cycle of a vehicle. Material type influences design factors such as part manufacturability, part weight, durability and useful life, and part reuse and recyclability. These factors strongly control environmental burden. Competition among materials often is vigorous for certain applications; however, in other applications (e.g., tires, frames, and windshields), material usage has been static for decades.

A recent Delphi study by the University of Michigan Office for the Study of Automotive Transportation (OSAT) reported that automotive manufacturers base their material decisions on several criteria including materials and processing costs, weight, warranty cost, corrosion resistance, design/styling requirements, environmental issues, perceived safety, customer vehicle preferences, disposal cost, recyclability, formability, and ease of final disposition.[11]

TABLE 7.3. OPTIONS FOR INTERNALIZING ENVIRONMENTAL COSTS OF PRODUCTS

Life Cycle Stage	Regulatory Instruments	Economic Instruments
Raw Material Extraction and Processing	• Regulate mining, oil, and gas nonhazardous solid wastes under Resource Conservation and Recovery Act (RCRA) • Establish depletion quotas on extraction and import of virgin material	• Eliminate special tax treatment for extraction of virgin materials, and subsidies for agriculture • Tax the production of virgin material
Manufacturing	• Tighten regulations under Clean Air Act, Clean Water Act, and RCRA • Regulate nonhazardous industrial waste under RCRA • Mandate disclosure of toxic materials use • Raise CAFE Standards for automobiles • Mandate recycled content in products • Mandate manufacturer take-back and recycling of products • Regulate product composition, e.g., volatile organic compounds (VOCs) or heavy metals • Establish requirements for product reuse, recyclability, or biodegradability • Ban or phase out hazardous chemicals	• Tax industrial emissions, effluents, and hazardous wastes • Establish tradable emissions permits • Tax the carbon content of fuels • Establish tradable recycling credits • Tax the use of virgin toxic materials • Create tax credits for use of recycled materials • Establish a grant fund for clean technology research
Purchase, Use, and Disposal	• Mandate consumer separation of materials for recycling	• Establish weight/volume-based waste disposal fees • Tax hazardous or hard-to-dispose products • Establish a deposit-refund system for packaging or hazardous products • Establish a fee/rebate system based on a product's energy efficiency • Tax gasoline
Waste Management	• Tighten regulation of waste management facilities under RCRA • Ban disposal of hazardous products in landfills and incinerators • Mandate recycling diversion rates for various materials • Exempt recyclers of hazardous wastes from RCRA Subtitle C • Establish a moratorium on construction of new landfills and incinerators	• Tax emissions or effluents from waste management facilities • Establish surcharges on wastes delivered to landfills or incinerators

Source: Ref. 8.

Other factors influencing material selection which were not included in the Delphi survey are regulations and many additional performance criteria. The diversity of these parameters and the lack of a comprehensive decision-making framework illustrates the difficulty and complexity of the material selection process.

Ashby[12] described material selection as an activity that enters at every stage of the design process, but the nature of data for the material properties required at each stage differs greatly in level of precision and breadth. The material selection charts used by Ashby narrow the range of materials that maximize the performance of the component. Several studies[13–17] have addressed material selection as a tradeoff among several interrelated and complex criteria provided above. These studies have investigated only discrete aspects of the material selection process rather than performing a complete systems analysis of the material life cycle.

Currently, automobile manufacturers use checklists, requirement matrices, and design guidelines as preliminary screens for materials that meet engineering material specifications. At present, OEMs have guidelines that list materials of concern which should be avoided. Vehicle recycling guidelines address fasteners, labeling, recycled content, and other recyclability issues. It is a challenge to create guidelines and checklists that are specific, practical, and at the same time do not lead to unresolvable conflicts with other life cycle objectives.

7.3.2 *Life Cycle Assessment and Material Selection*

Several investigators[2–4,13–15,18–23] have applied life cycle assessment tools to analyze material alternatives. In the early 1980s, several studies[13,14,24,25] began to analyze life cycle energy requirements of alternative materials for automotive applications. Material production and fabrication energies were evaluated and compared to the relative contribution of a part or component to the total fuel consumption by the vehicle in operation. These analyses provided an indication of the potential energy savings resulting from mass reduction by using lightweight materials. More recently, investigations have focused on material selection in body-in-white applications,[2,4,20,22] fascia,[18] air intake manifolds,[23] and the front end.[26]

The effects of material substitution on life cycle energy depend on several key parameters, including the material production and fabrication energies and the fuel-efficiency-to-mass correlation for the vehicle under study. A sensitivity analysis for material substitution was conducted by Sullivan and Hu[4] in which they derived the following simplified equation:

$$\Delta E_{tot} \cong \left(\frac{\frac{E'_i}{C_i} - f\frac{E'_k}{C_k}}{1-f} + \frac{dE_{op}}{dp_T} \right) \Delta p_T$$

where

ΔE_{tot} = life cycle energy differences from replacement of material i with material k
E'_i = material production energy for i
E'_k = material production energy for k
f = substitution factor of material k for material i
C_i, C_k = production efficiency of fabricating part of material i and material k (accounts for offal)
E_{op} = vehicle operation energy
p_T = total mass of vehicle
Δp_T = vehicle weight savings from replacement of material i with material k

This equation clearly shows the relationship between specific material production energies, the lightweighting effect on fuel consumption (dE_{op}/dp_T), and the total weight savings achieved Δp_T. If the lightweighting effect (dE_{op}/dp_T) is low, then the material production energy can have a more dominant contribution to the life cycle energy and can overshadow gains in the reduction of operational energy. Sullivan and Hu[4] provided specific examples of life cycle energy versus weight reduction for Al and fiber-reinforced plastics relative to a steel-intensive vehicle.

Teulon, Boidot-Forget, and Epelly[27] also indicated limits in reducing life cycle energy from lightweighting the vehicle. They found that a high-strength steel frame consumed less life cycle energy compared to a lighter Al frame when a vehicle with a high lightweighting effect (0.75 l/100 km per 100 kg) was evaluated.

Several barriers currently limit the widespread use of life cycle assessment: data availability, product development cycle time constraints, costs, and impact assessment methods for classification and valuation. The major limitation hindering practical application of life cycle inventory analysis is data availability. In the United States, four databases owned by consultants are now being used for life cycle inventory analysis: Boustead, Chem Systems, Ecobalance, and Franklin. Several efforts have been undertaken recently to develop databases for material production (i.e., U.S. Advanced Materials Partnership, American Plastics Council, and U.S. Department of Energy). No publicly available life cycle databases exist, although the U.S. Department of Energy is developing a materials database (LCAD). Most life cycle inventories and energy analyses have been conducted as part of planning and long-range development rather than as on-line tools for designers. Lack of readily available data precludes comprehensive analysis on a routine basis for design engineers.

7.3.3 *Life Cycle Design*

The Life Cycle Design program, sponsored by the EPA Risk Management Research Laboratory, has initiated four demonstration projects that involve automotive applications. The emphasis of the research is on the development and integration of practical tools to enhance design decision-making. A life cycle design project with Ford focuses on a comparative assessment of aluminum and nylon intake manifolds.[23] Initial results from a comparison of alternative sand-cast and multitube brazed aluminum manifold designs document several tradeoffs that exist with respect to environmental impacts, performance, and costs to individual life cycle stakeholders. Steel and HDPE plastic fuel tanks are being studied in a collaborative research project with GM. Application of the life cycle design framework to automotive films is being tested by 3M. Cost, performance, and legal and environmental requirements for each part are being evaluated using multicriteria matrices. Inventory analyses and life cycle cost analyses also are being conducted to support design decision-making.

Priority in design is now given to performance requirements, cost considerations, and satisfying regulations. A life cycle cost analysis shows the relationship between costs and individual stakeholders, including manufacturers, customers, and end-of-life managers. Table 7.4 shows operating costs for a typical vehicle.

The average price of a new automobile in 1994 was $19,676 (domestic $18,361 and import $24,595). In 1993 the price was $18,716, and the annual median family earnings was reported as $36,764.[28] The cost of gasoline based on an average fuel economy of 28.2 mpg,[28] fuel price of $1.17,[29] and 120,000-mile useful life would be $4,979. The total estimated costs to dismantlers and shredders for procurement and processing of a 1984 vehicle using data presented in Table 6.7 of Chapter 6 is $262.22, and the net residual value for parts and materials is $340.75. These data and the data in Table 7.4 indicate the relative magnitude of principal life cycle costs incurred by customers and end-of-life managers. It is not surprising that, without regulatory pressures, OEMs have focused their resources on manufacturability and customer requirements rather than on environmental issues.

Innovative vehicle designs such as hypercars and ultralights offer the greatest potential for improving the life cycle of the automobile. Rigorous life cycle inventory analyses of these designs and concepts have not been performed, but the proposed achievements in fuel economy and mass reduction are expected to lead to a dramatic improvement in the life cycle environmental profile of the automobile.

A recent publication by Lovins *et al.*[30] analyzes the hypercar system in depth, although technical information was not organized or evaluated explicitly from a life cycle perspective. Two recent publications from the Society of Automotive Engineers have explored the future of automobile technology and have reviewed progress made in the development of alternative vehicles.[31,32] Use-phase environmental issues were emphasized with some discussions on vehicle

TABLE 7.4. OPERATING COSTS FOR A TYPICAL 1995 VEHICLE, CENTS PER MILE

	Type of Cost	Cents per Mile
Fixed[a]		
	Depreciation (6 yrs or 60,000 mi)	25.4
	Insurance	5.9
	Finance Charge	5.9
	License, Registration, Taxes	1.7
	Subtotal	38.9
Variable		
	Gas and Oil	6.0
	Maintenance	2.6
	Tires	1.4
	Subtotal	10.0
Total Operating		48.9

[a] Fixed costs for depreciation, insurance, finance charge, and license fees were estimated from the total fixed cost per mile and itemized data for the annual fixed cost.

Source: Ref. 28.

retirement. Potential tradeoffs related to customer requirements such as safety, interior space, and acceleration were considered. Alternative fuels and alternative vehicles were addressed thoroughly, but life cycle environmental impacts were not evaluated or discussed.

Perhaps the greatest driver that will accelerate the development of innovative automobile technology is the emerging market for automobiles by industrializing nations. Projections for the automobile industry indicate that the current design of the vehicle is not sustainable on a global scale.[32] Significant expansion in the world population of automobiles would rapidly exhaust petroleum reserves. Consequently, factors affecting the sustainability of automotive industry growth may help in forcing radical improvements.

Given the complexity of design requirements influencing automobiles, the value of life cycle design tools such as multicriteria matrices for analyzing environmental, performance, and cost tradeoffs for current and future vehicle design becomes apparent.

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Chapter 8

Summary and Conclusions

This book characterizes environmental burdens presently associated with the automobile life cycle and reviews opportunities for reducing those burdens in the future through design and management initiatives by industry and government policy reforms. This investigation was undertaken as a collaboration of multistakeholders including industry, government, environmental organizations, and academia. As authors of this study, we synthesized information and attempted to fill gaps that were not addressed during the Industrial Ecology of the Automobile Seminar Series. The multistakeholder process proved constructive in identifying common and divergent perspectives. Most importantly, this book provided a framework for understanding the complexity of issues that influence the life cycle of the automobile. Furthermore, this book can provide guidance for implementing actions for improvement. In the future, the life cycle framework will continue to help organize and display improved data and information.

Key stakeholders responsible for management of the automobile life cycle are material suppliers, parts fabricators, OEMs, consumers, service and repair professionals, dismantlers, shredders, nonferrous processors, waste managers, regulators, insurers, and investors. The primary actors affecting the life cycle are OEMs, consumers, and government. For example:

- Consumers have the greatest responsibility in influencing the environmental profile of the automobile through their purchasing power, driving behavior, and maintenance habits.
- The OEMs have the greatest responsibility in shaping the environmental profile of the automobile through design. The OEMs must respond to consumer demand, but they also can influence consumer behavior toward a more sustainable transportation system.
- Government is responsible for establishing the regulatory framework that sets standards for environmental management of the automobile life cycle system. Government addresses environmental management at global, national, regional, and local levels. Specific policies, particularly at the national and international level, should include goals and targets for improvement to guide businesses on issues such as energy consumption and greenhouse gas emissions.

The most significant environmental improvement in the automobile will be realized when the key stakeholders more fully understand the major environmental consequences related to the automobile life cycle and consequently assign them higher priority in decision-making. At present, the U.S. market system does not effectively encourage environmental improvements because of incomplete pricing of environmental impacts such as nonrenewable energy depletion and pollutant and greenhouse gas emissions. The life cycle framework serves as a tool to address the complex set of technical, economic, ecological, political, and social issues influencing the automobile life cycle.

Conclusions will be presented in two parts. First, the conclusions regarding the inventory characterization of the automobile life cycle will be provided. Second, conclusions related to opportunities for improving the environmental profile of the automobile life cycle will be offered as recommendations.

8.1 Characterization of Automobile Life Cycle Environmental Burdens

Characterization of environmental burdens associated with the automobile life cycle as presented in this book is limited by the availability and quality of published data. This book is a compilation of recent life cycle inventory data from a broad range of literature. Gaps in the data were identified. Key findings are provided here, but more specific results are presented in the body of the book.

8.1.1 Automobile Environmental Burdens on a National Basis

Materials

Data presented in Chapter 3 clearly demonstrate the material intensity of the automobile sector of the economy. The automotive industry in the United States represents at least one-third of the overall U.S. consumption of iron (34.5%), lead (69.5%), platinum (41.4%), natural rubber (74.7%), and synthetic rubber (41.4%).[1] Approximately 43.2% of ferrous metals and 60 to 70% of aluminum in new vehicles come from recycled material.[2,3] This yields a recycled content for an average vehicle of approximately 33%, with the balance of materials being produced from virgin (primary) sources.

Energy

The energy intensity of the automobile is clearly established in Chapter 5. The current propulsion system of automobiles relies on a nonrenewable energy source. Adequacy of the petroleum stock is estimated to last 50 to 60 years, based on current reserves and consumption rates.[4,5] Furthermore, U.S. dependence on imported petroleum is greater than 40%,[6] and the U.S. Department of Energy (DOE) projects that oil imports will reach 57% by the year 2005.[7] Automobiles and light trucks account for 59% of transportation energy consumed in the United States; the transportation sector accounted for 27.3% of total U.S. energy use in 1992.[8]

Vehicle miles traveled (VMT) for automobiles (passenger cars and motorcycles) has increased at an average annual rate of 2.6% between 1970 and 1992. The VMT for light-duty trucks has increased at an average annual rate of 6.3% during this same period.[6] In addition, energy consumption is expected to increase if the trend continues for consumers to purchase more light-duty trucks and sport-utility vehicles instead of passenger vehicles.

Emissions

In 1994, highway vehicles, which include passenger cars, light trucks, motorcycles, and other heavy-duty vehicles such as trucks and buses, accounted for 62% of CO, 32% of NO_x, 27% of VOCs, 0.68% of PM-10 (particulate matter less than 10 microns; a miscellaneous category consisting of agriculture, other combustion and fugitive dust from roads and other sources accounted for 88% of PM-10 emissions), and 28% of lead emissions from all U.S. sources.[9] By 1994, unleaded gasoline sales accounted for 99% of the gasoline market; under the Clean Air Act Amendments (CAAA), leaded gasoline was prohibited for use in highway vehicles after December 31, 1995.

The contribution of highway vehicles to total emissions in urban areas is significantly higher: 74% of CO, 46% of NO_x, and 33% of VOCs.[10] Ozone, the major urban air quality problem, is formed by the reaction between NO_x and VOCs in the presence of sunlight. Automobiles emissions are partially responsible for twenty-two serious nonattainment areas for ozone, two serious nonattainment areas for CO, and six serious nonattainment areas for PM-10.

In 1993, 98.7 million lbs of Toxic Release Inventory (TRI) releases and 168 million lbs of TRI transfers were reported from Motor Vehicle (SIC code 371) facilities. Emissions from painting operations have been estimated to account for 56% of all TRI releases and transfers. Additional TRI emissions should be allocated to the automobile life cycle for the production of automotive materials from the petroleum refining, chemicals, plastics, and primary metals sectors.

Combustion of gasoline by automobiles is responsible for a significant fraction of greenhouse gas emissions in the United States. Fuel combustion associated with automobiles and light-duty trucks accounted for 19% of total U.S. CO_2 emissions in 1991.[6]

Waste

Approximately 94% of retired vehicles are currently processed for recycling. Each year, 2.5 to 3 million tons of automobile shredder residue (ASR) are generated each year, consisting of plastics, rubber (mostly tires), glass, and other materials such as dirt. ASR currently accounts for 1.3 to 1.5% of municipal solid waste (MSW) in the United States.[11]

8.1.2 Environmental Burdens on a Unit-Vehicle Basis

Materials

The material composition by weight of a typical 1994 vehicle is 1739 lbs of steel (54.8%), 408 lbs of iron (12.9%), 246 lbs of plastics (7.7%), 190 lbs of fluids and lubricants (6.0%), 182 lbs of aluminum (5.7%), 134 lbs of rubber (4.2%), 89 lbs of glass (2.8%), 42 lbs of copper and brass (1.3%), 27 lbs of powder metal parts (0.9%), 16 lbs of zinc die castings (0.5%), and 99 lbs of other materials (3.1%), constituting a total weight of 3171 lbs.[1]

Energy

The life cycle energy consumption for typical vehicles has been estimated to range from approximately 350 GJ for a 650-kg car over a useful life of 120,000 km to 1650 GJ for a 2000-kg car with a useful life of 200,000 km.[12] Studies of various intermediate-sized vehicles indicate average life cycle energy use of approximately 700 GJ. Some of these studies address only production and operation energies; others also include energy consumed for maintenance, infrastructure, and retirement. Use-phase energy consumption accounts for approximately 90% of total life cycle energy consumption for a typical vehicle.[12–15]

Emissions

Tier 1 standards for passenger vehicles are 0.25 g/mi for HC, 3.4 g/mi for CO, and 0.4 g/mi for NO_x. However, studies demonstrate that vehicle emissions throughout an operating lifetime are significantly greater than those projected from new-car certification standards. Preliminary data from An, Barth, and Ross[16] indicate that average exhaust emission factors during a vehicle lifetime for late-1980s and early-1990s light-duty vehicles are approximately 16 g/mi for CO, 0.9 g/mi for HC, and 1.4 g/mi for NO_x. Thus, an average light-duty vehicle will emit approximately 2100 kg of CO, 120 kg of HC, and 190 kg of NO_x throughout its lifetime. High-power operation, stabilized running, and cold/hot starts each account for 30 to 37% of CO emissions. For HC emissions, stabilized running and cold start dominate, with approximately 85% of the total. Stabilized running and high-power operation dominate NO_x emissions, accounting for approximately 75% of the total.

Greenhouse gas emissions from a light-duty, combustion-engine vehicle using reformulated gasoline were estimated at 491.2 g/mi CO_2 equivalents (333.7 g/mi for vehicle use, 101.6 g/mi for fuel production, 14.0 g/mi for car assembly, and 41.9 g/mi for materials production).[17]

A study by Schuckert *et al.*[12] of life cycle primary pollutants shows that CO emissions are concentrated in the use phase, but other pollutant emissions such as methane, NO_x, and SO_2 are more evenly distributed among manufacturing, use, and fuel production activities. Vehicle emissions for this study were much lower than those reported by An, Barth, and Ross[16] for actual operating conditions.

Waste

Parts are recovered during dismantling of retired vehicles, depending on the condition of the parts, economics for recovery, and market demand. Clutches, water pumps, engines, starters, alternators, and motors for power windows frequently are removed and remanufactured as replacement parts. Batteries also are removed, and the lead in them is recycled. It is reported that approximately 75% of the vehicle is recycled. Shredding of the vehicle hulk produces three major fractions: ferrous, nonferrous, and ASR. Based on the material content of a typical 1984 vehicle, this would yield 2201 lbs of ferrous (70.1%), 245.5 lbs of nonferrous (7.8%), and 695.0 lbs of nonmetallics (22.1%). Assuming a 95% recovery of metallics, 74% of the vehicle would be recovered. Currently, several other components being recovered include engine oil, coolants, refrigerants, and approximately 37% of tires. Residual fluids and mercury from switches present environmental problems in end-of-life management. These issues are being addressed through the Vehicle Recycling Partnership and the Michigan Mercury Pollution Prevention Task Force.

8.1.3 Trends in Automobile Environmental Burdens

Significant environmental improvements in vehicle design and production have been achieved. However, many of these improvements have not been translated directly into an overall reduction in environmental burdens associated with automobile use because of customer demand for less-fuel-efficient vehicles (such as light trucks or high-performance automobiles) and increased VMT. If these patterns in customer demand and usage continue, overall environmental burdens associated with automobile use are expected to increase unless more dramatic changes in vehicle design are implemented.

Materials

Between 1980 and 1990, the average weight of a typical vehicle decreased by 14%. Since 1990, this trend has reversed and the average vehicle weight has increased by 10% from 1990 to 1994.[6] This weight increase partially offsets technological gains that have been made to improve fuel economy.

Energy

Between 1978 and 1988, sales-weighted corporate average fuel economy (CAFE) for domestic automobiles improved from 18.7 to 27.4 mpg. Since then, no significant improvements have been achieved.[6] As light-truck sales continue to capture more market share, the combined, sales-weighted CAFE average of cars and light trucks will decrease. In 1988, the combined, sales-weighted average CAFE for light trucks and cars was 26.4 mpg, compared to 25.4 mpg in 1993. A recent forecast by the University of Michigan Office for the Study of Automotive Transportation, based on a survey of the automotive industry, projects that fuel economy will increase to 35 mpg for five-passenger cars by the year 2010 (assuming that factors such as price, safety, convenience, range, and performance are on parity with those of today's vehicles).[18]

For highway vehicles, VMT growth averaged 3.3% compounded annually between 1970 and 1990. A lower growth of 2.3% was observed for the first five years of the 1990s. VMT is forecasted to increase at an annual rate of 2.15 to 2.37% during the next twenty years.[19]

Emissions

Significant progress has been made in reducing tailpipe emissions from light-duty vehicles through more stringent new-vehicle certification standards. Current standards represent a substantial reduction in exhaust emissions from 1960 base-level emissions of 10.6 g/mi hydrocarbons, 84 g/mi CO, and 4.1 g/mi NO_x. Standards plateaued in the early 1980s until recently. Elevated ozone levels remain a major problem that contributes to exceedance in noncompliance regions. For this reason, in 1994 emissions standards for HC were lowered from 0.41 to 0.25 g/mi, and standards for NO_x were reduced from 1.0 to 0.4 g/mi.[20] Degradation of in-use emissions over a vehicle's lifetime also represents an area for further improvement. The stricter standards of the California Air Resources Board are expected to drive further reductions. The Northeast states and the automotive industry are discussing a program that would result in the following future emissions standards: 0.075 g/mi for HC, 3.4 g/mi for CO, and 0.2 g/mi for NO_x.

Waste

The plastic and plastic composites fraction of the automobile increased from 195 to 246 lbs per vehicle between 1980 and 1994 model years. Other materials that currently constitute ASR did not change significantly during that period. Plastics offer the potential for lightweighting the vehicle; accordingly, plastics present a tradeoff between fuel savings and solid waste generation. This tradeoff aside, the potential for material and/or energy recovery from plastic parts and components remains essentially unrealized. The Vehicle Recycling Partnership under the U.S. Council for Automotive Research (USCAR) is actively seeking to improve end-of-life management of the automobile through various research and demonstration projects.

Limitations of Inventory

Publicly available databases to develop automobile life cycle inventories are severely inadequate. Several efforts by industry and government are beginning to address this limitation. Ultimately, the construction of any database will depend on businesses providing inventory data for unit processes on a product weight basis. In addition, government reporting requirements and industry data management systems should better support life cycle inventory data compilation. Efforts by the U.S. Auto Materials Partnership (USAMP) are critical toward database development, which also will benefit other consumer product sectors.

Efforts to overcome the following problems also would improve the characterization and inventory of the automobile life cycle:

- Mining and material processing inventory data are not well established in the public domain.
- Published environmental data on part fabrication and vehicle assembly processes are limited.
- The discrepancy between model predictions from EPA Mobile 5.0 and actual on-road performance over the life of a vehicle strongly limits the evaluation of use phase emissions.
- Inventory data for the type and quantity of parts recovered from dismantling and you-pull-it operations are not available. Computerized inventory databases are available for large dismantling wholesale/retail operations, but this data has not been compiled and reported in the literature.
- Recent field data should be collected from automobile shredding operations that track the material composition for ferrous, nonferrous, and ASR fractions from an automobile hulk.

This investigation used published inventory data to characterize the automobile life cycle. Available data from many different sources was used to construct a preliminary environmental profile of the automobile. This characterization does not represent a rigorous life cycle inventory analysis of a typical automobile but begins to demonstrate how environmental burdens are distributed across the life cycle. Interpretation of the results should recognize the shortcomings outlined above. In addition, further valuation and interpretation of the limited inventory data presented here requires application of impact assessment techniques that are outside the scope of this study.

8.2 Recommendations

Based on current levels of nonrenewable resource use and emissions of greenhouse gases and other pollutants associated with the automobile, the conventional automobile and its current use patterns do not appear sustainable. The United Nations World Commission on Environment and Development defines sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Various guidelines and principles for sustainable development are being proposed. The following guidelines from the Scottish Natural Heritage, which are similar to the goals of life cycle design presented in Chapter 2, are an example of contemporary thinking in this area[21]:

1. Nonrenewable resources should be used wisely and sparingly at a rate that does not restrict the options of future generations.
2. Renewable resources should be used within the capacity of their regeneration.
3. The quality of the whole natural heritage should be maintained and improved.
4. In situations of great complexity or uncertainty, the precautionary principle should apply.
5. An equitable distribution of the costs and benefits should accompany any development.

Declining petroleum stocks and declining resource quality of many metallic ores demonstrate how present patterns of automobile use contravene Guideline 1. Land conversion through urban sprawl, which includes highway infrastructure, degrades our natural heritage as addressed in Guideline 3. The Michigan Relative Risk Analysis Project ranked absence of land use planning that considers resources and the integrity of ecosystems among the highest relative risks to Michigan's environment.[22] California gives a high risk rank to urban sprawl and mobile source releases to air.[23] A substantial lag exists between mitigation of greenhouse gas emissions and stabilization of the climate system because of the long residence times of greenhouse gases. According to Guideline 4, the uncertain but potentially catastrophic consequences of global warming warrant strong action to limit greenhouse gas emissions from automobile fuel combustion. The Intergovernmental Panel on Climate Change (IPCC) recently published findings and recommendations concerning the transportation sector in its Second Assessment Report.[24] This report indicated that global transportation energy use is projected to grow to 90–140 EJ in 2025 from an estimated 61–65 EJ in 1990 unless new measures are taken. Greenhouse gas emissions may be reduced by as much as 40% of projected 2025 levels if a combination of measures are taken, including significant improvements in the vehicle efficiency; increased use of smaller vehicles, altered land-use patterns, transport systems, mobility patterns, and lifestyles; shifting to less energy-intensive transport modes; and the use of alternative fuels and electricity from renewable sources. All these factors are compounded by the anticipated demand for new vehicles from developing countries. As globalization of the market occurs, the enormous disparities in resource consumption and emissions between the United States and developing countries must be addressed, as stated in Guideline 5.

Significant changes in the design of current automobiles are necessary if the automobile is to emerge as a sustainable solution to personal transportation on a global scale. Bold measures are required to address these challenges. Incremental improvements by industry alone may not be effective in achieving a sustainable automobile design. The industrial ecologist may emphasize a different pathway to sustainable transportation by promoting more efficient means of public transportation.

Whether change occurs incrementally or through leapfrog approaches, the entire product life cycle must be addressed. The automobile life cycle system can be organized into product and process components. The product material (e.g., steel, aluminum, plastics, rubber, and glass) is transformed across each stage by a process component at that stage. The product material entering the next stage has inherent characteristics that influence the behavior of the product component at that phase. The process component at that stage can be viewed as an independent system and has a unique set of requirements that influences its behavior. The process activities and principal components for the automobile life cycle, in consecutive order, are as follow: mining (mining equipment), drilling, materials processing (steel mills and chemical plants), parts fabrication (molding and stamping equipment and facilities), assembly (equipment and assembly plant), use (vehicle and the infrastructure which includes roads and gas stations), service (body shops and repair shops), dismantling (salvage yards and wholesale/retail dismantling operations), shredding (shredder), nonferrous separation and recovery (nonferrous processor), and management of residual materials (landfill and incineration with energy recovery). Some of the process components for the automobile, such as those in the materials production and use phases, also serve a wide range of other products.

Opportunities to improve the automobile exist at each stage of the life cycle. Process improvements for a given stage often can be made independently, without affecting other stages. Alternately, product design changes can be made that may be integrated with process design changes at one or more stages of the life cycle. Product and process changes that involve multiple stages of the life cycle will require partnership approaches to effectively implement.

Specific findings and recommendations that are relevant to consumers, policy-makers/regulators, and automobile manufacturers are discussed in the next section. Ultimately, market failures caused by the public's lack of environmental information and by pricing that does not reflect the full environmental costs of automobile production, use, and retirement must be corrected to promote accelerated environmental improvements and to move automobile use toward sustainability.

8.2.1 Consumers

Consumers have a major role in reducing the environmental impacts associated with owning and operating automobiles. Consumer purchases of new and used vehicles, coupled with VMT, are the market forces that determine the life cycle of the automobile. The following potential opportunities represent actions and decisions that consumers can take to reduce not only use phase burdens but total life cycle burdens.

Reduce the Demand for Passenger Travel

Vehicle miles traveled have been increasing continuously. This trend offsets technological achievements made to improve fuel economy. Several ways to reduce VMT include better urban planning (preventing urban sprawl), telecommuting, and better planning of trips.

Use Alternative Modes that Are More Efficient than the Automobile

Transit modes such as buses, trains, motorcycles, and bicycles can be less energy-intensive options for personal transportation. These alternatives each have significant advantages and disadvantages with respect to convenience, accessibility, reliability, safety, comfort, space, noise, potential for social interaction versus privacy, and cost. The potential energy savings and overall environmental burden reduction of mass transit systems depend directly on the passenger load factor. Greater potential for mass transit is achieved as the passenger load approaches maximum capacity.

Car Pool

Occupancy has decreased from 1.9 persons per vehicle in 1977 to 1.6 persons per vehicle in 1990. For work trips, vehicle occupancy is approaching its theoretical minimum; it was 1.1 in 1990.[6]

Purchase New And Used Automobiles that Are More Fuel Efficient and Less Polluting

By demanding more ecoefficient vehicles, consumers can effectively reduce burdens in the use phase of the automobile product life cycle. Customers may choose to avoid buying vehicles with environmentally costly attributes that do not generally fit their needs, such as high-powered engines, four-wheel drive, and large cargo capacity. Short-term rentals can satisfy many limited needs that are now met by purchasing vehicles.

A list of fuel economies for new vehicles is published each year by the EPA and DOE. In 1995, these data showed that fuel economy for models with a five-speed manual transmission was 0 to 10% greater than for the same models with a four-speed, link-up automatic transmission.[25] Manual transmissions generally have lower friction, resulting in a higher fuel efficiency than automatic transmissions. Old vehicles generally are more polluting than new vehicles and should be retired if retirement is economically feasible.

Improve Vehicle Operation Practices

Many opportunities exist to reduce burdens through changes in driving practices. The following list represents some of these approaches:

- Avoid congestion when possible (idling in traffic wastes time and energy)
- Drive at the most efficient speed (30 to 40 mph is the most energy-efficient speed for 1984 vehicles; decreasing driving speed from 70 to 55 mph resulted in a 25.7% energy savings)
- Avoid rapid acceleration and deceleration (fuel economy and emissions suffer)
- Windows down versus air conditioning (a study indicated that air conditioning had a greater reduction on fuel economy compared to windows-down driving for 1980-era automobiles, which are now virtually all retired; whether this relationship continues to hold for modern, aerodynamic designs should be studied)
- Carrying unnecessary weight in vehicles wastes fuel
- Turn off the engine rather than allow it to idle for longer than a minute

Vehicle Maintenance

Proper maintenance is important for extending the useful life of parts, components, and the vehicle system. It also can enhance fuel economy and reduce vehicle emissions. The following actions should be taken:

- Keep tires properly inflated (15 psi rather than 26 psi lowers fuel economy by approximately 3.3%)
- Check wheel alignment
- Maintain proper engine adjustments
- Avoid excessive vehicle washing
- Keep good records on vehicle maintenance to facilitate decisions on servicing of parts and components and when to retire the vehicle

In addition, maintenance practices recommended by OEMs provide general guidance to vehicles owners.

The advantages of many of these approaches are well established. Lack of information may limit consumer actions toward reducing automobile and/or transportation-related environmental burdens. Information can be made more readily available through education at primary, secondary, and higher education levels and through ecolabeling and advertising. Advertising by OEMs currently emphasizes attributes that are not environmentally preferable, such as speed, power, and large size. More significant are other values, factors, and forces that influence consumer behavior, such as convenience, independence, comfort, and opportunity costs.

8.2.2 Policy-makers

Government regulations and economic instruments influence the automobile life cycle and the relative success of alternative modes of transportation. In addition, government sponsors research and development to advance technological solutions to environmental problems.

CAFE and vehicle emission standards are examples of regulations strongly influencing automobile design. The regulatory framework also strongly influences the manufacturing stage of the automobile. Historically, an adversarial relationship has existed between government regulators and industry. Currently, several innovative partnerships between industry and government, such as the EPA Common Sense Initiative and the Partnership for a New Generation of Vehicles (PNGV), are providing a foundation for a more constructive relationship for both parties. Government and industry are exploring more flexibility in regulations to promote pollution prevention and life cycle management.

More effective coordination between government regulatory and technology development programs is necessary to eliminate duplicative and potentially counterproductive efforts.

More stringent regulations for each life cycle stage should continue as long as this results in a cost-effective reduction in burdens for a particular stage and does not shift environmental impacts upstream or downstream from that stage. The following stage-specific actions are recommended:

Material Acquisition and Processing

Revision of the mining laws to better reflect the value of mineral resources would promote more efficient use of virgin and secondary materials. In particular, the General Mining Law of 1872 should be revised to discontinue subsidizing the price of virgin minerals.

Manufacturing

The Automotive Manufacturing Sector Project under the EPA Common Sense Initiative signifies an important opportunity to move beyond the adversarial relationship between industry and government. This project seeks to improve the regulatory framework through a partnership approach. Identifying specific regulatory reforms will be a major challenge for this project.

Use

Current market conditions and regulations fail to address the continuing increase in fuel consumption and greenhouse gas emissions, which are linked to VMT. The most direct mechanism for curbing the growth in VMT and total fuel consumption is to raise the price of gasoline. The effectiveness of the market-driven approach was demonstrated by the oil shocks of the 1970s. The U.S. price of gasoline in constant dollars is at or near its historic lowest level,[26] which is not logical for a nonrenewable resource expected to be depleted in the next century. A gasoline tax would internalize the full costs of petroleum acquisition and use. In addition, this action could bring the costs of gasoline closer to \$3.50/gal, which would be more consistent with its current price in most European countries and Japan. Increased price would create an incentive for U.S. customers to purchase more fuel-efficient vehicles and to drive fewer miles. However, substantially increasing gasoline prices above the market rate does not seem politically possible at present. Incremental increases in a gas tax during a specified period and/or provisions that address social regressivity would minimize economic disruptions. Raising the price of gasoline also would allow more efficient modes of transportation, such as buses and rail, to compete more effectively with the automobile.

Corporate average fuel economy (CAFE) has been effective in raising fuel economy and maintaining it at its current level. The ability of CAFE to control fuel economy is shown by the strong correlation between sales-weighted average fuel economy and the CAFE standard. However, as light-duty truck sales increase, fleet average fuel economy will decrease. No regulatory mechanism currently is in place to prevent decline in the combined average passenger and light-duty truck fuel economy. A combined light-duty (passenger cars and trucks) CAFE standard should be implemented. In addition, the combined light-duty CAFE standard should increase steadily to address global warming and the depletion of petroleum in the absence of a major increase in the price of fuel. However, increasing the average fuel economy through CAFE standards will provide users the means to travel greater distances per dollar expended on fuel. Therefore, VMT can be expected to rise in conjunction with CAFE.

Relying exclusively on either CAFE to reduce fuel consumption or market forces to raise the price of gasoline has its shortcomings. At present, low market prices for gasoline and modest CAFE standards provide little incentive for improvements in fuel economy. To more effectively manage our petroleum energy supply and to mitigate the environmental consequences of its use, CAFE standards and fuel prices must increase steadily. This combination of forces appears to be the most feasible policy option.

Because of the negative effect on fuel economy and safety, it may be wise to reverse federal and state actions to relax speed limits.

Education programs will be essential to inform the public about the environmental consequences of gasoline use. Public understanding of these adverse environmental consequences is essential to generate support for a gasoline tax and/or to encourage consumers to purchase more fuel-efficient vehicles.

The major driving forces for alternative fuel use are as follow:

- **Near term:** Improvement in air quality and reduction in greenhouse gas emissions. Air quality benefits depend on the nature of emission standards promulgated for alternative fuel vehicles and on the tradeoffs vehicle designers make among factors such as emissions, vehicle performance, and fuel economy. Near-term benefit in greenhouse gas emissions through alternative fuel use is expected to be small unless design decisions are controlled by strong incentives to reduce greenhouse gas emissions from the entire fuel cycle.[27]
- **Long term:** The need for alternative sources of energy as petroleum resources diminish. The energy, national security, and economic benefits from reducing oil use and imports are major drivers for governmental actions to promote alternative fuels.

The advantages and disadvantages of each alternative fuel are presented in the design section of this book. The timing for complete transition to alternative fuel is too difficult to predict, although a rough estimate for the upper limit would be approximately 60 years, which is the projected adequacy of gasoline fuel reserves.

Several factors inhibit the introduction of alternative fuels into the marketplace: the entrenchment of gasoline in the light-duty vehicle market, the lack of supply infrastructure, mature vehicle technologies for most of the alternative fuels, and various cost and range problems. Liquid fuels are most compatible with the existing distribution systems and engines. All alternative fuels are less dense than gasoline and thus need a higher volume of fuel to achieve an equivalent range.[27]

Gasoline prices in the United States today are at or near their historic lowest level, adjusted for inflation.[26] Gasoline prices are two to three times higher in all other parts of the world. Low prices make it difficult for some alternative fuels to compete with gasoline. The cost of alternative fuels such as compressed natural gas (CNG) and hydrogen are high because of different storage and combustion requirements. Although liquid alternative fuels have storage requirements similar to those of gasoline, they generally are more expensive to produce than gasoline.

Federal and state governments have initiated numerous important policy initiatives to move alternative fuels into the U.S. motor vehicle fleet.[27] These incentives include the following:

- California's Low-Emission Vehicle Program under the CAAA, which requires minimum sales of vehicles in different emissions categories, including the year 2003 10% Zero-Emission Vehicle (ZEV) sales mandate (the 1998 mandate for 2% ZEV was rescinded by the California Air Resources Board in November 1995); California emission standards should address life cycle emissions associated with the full energy cycle for alternative vehicles
- Alternative fuel fleet requirements and tax incentives under the Energy Policy Act of 1992
- Fuel economy credits to OEMs toward meeting their CAFE requirements by manufacturing alternative fuel vehicles under the Alternative Motor Fuels Act of 1988 (most OEMs can comply with current CAFE standards without great difficulty and thus the availability of credits may have little effect unless CAFE requirements are raised)

However, fuel taxation policy does not appear to take rational account of alternative fuels' unique characteristics. The current policy taxes different fuels at rates that do not bear any relation to energy policy or environmental goals. For example, fuels such as electricity, natural gas, and ethanol receive favorable tax treatment. Others, such as propane and methanol, are penalized. Accordingly, the Office of Technology Assessment[27] gave two recommendations for alternative fuel policy:

- Tax each alternative fuel at the same rate in dollars per Btu delivered to the vehicle, possibly with electricity rates being adjusted to account for energy lost at the power plant. The rate could be equal to or lower than current gasoline taxes, to reflect the government's desire to allow the market to decide or to favor alternative fuels over gasoline.

- Tax each alternative fuel at different rates that reflect evaluations of each fuel's nonmarket characteristics (e.g., energy security implications and environmental characteristics).

From a life cycle perspective, a more comprehensive economic instrument also would address full fuel cycle energy and associated emissions. This approach would require an impact assessment valuation method such as the Environmental Priority Strategies (EPS) system for calculating environmental load units. A more practical but limited approach could develop a tax formula that would account for major impact categories such as energy and greenhouse gas emissions using a weighting factor.

Vehicle emissions have improved substantially during the last two decades, but they remain a major contributor to CO, NO_x, CO_2, and VOCs at a national level. Because ozone (formed by VOCs and NO_x) is the major cause of urban air quality problems, nonattainment of ozone in certain areas would suggest stricter emission standards.

Recent evidence indicates that human activities, primarily through the burning of fossil fuels, are partially responsible for changes in global climate. Without drastic steps to reduce greenhouse gas emissions, most specialists predict that the average global temperature will increase 1 to 3.5°C during the next century.[28] The combustion of nonrenewable fossil fuel which produces CO_2 may be one of the greatest threats facing sustainability of the automobile. The United States has not been aggressive in curbing its CO_2 output. A strong policy is needed to address this potentially catastrophic effect.

The climate treaty signed at the Rio de Janeiro Earth Summit in June 1992 required that developed countries only "aim" to return their greenhouse gas emissions to 1990 levels by the year 2000.[29] President Clinton's Climate Change Action Plan indicated that fossil-fueled vehicles constitute the fastest-growing source of carbon dioxide. The Clinton Administration has admitted that its plan is not on track to meet the goal of 1990 emission levels by the year 2000.[29] The American Petroleum Institute is strongly opposed to extending the Rio de Janeiro treaty beyond voluntary targets.

A 1995 interim report by the International Panel on Climate Change (IPCC) concluded that the climate treaty in its present form would not lead to a stabilized atmosphere. The panel's report indicated that stabilization can be achieved only if emissions are reduced well below 1990 levels. To overcome competitiveness concerns, the Netherlands advocates international measures to control greenhouse gas emissions rather than regulations at the national level.

Retirement

The following actions are recommended to reduce environmental burdens in the retirement stage:

- Mandate the removal of fluids and gas tanks from retired vehicles by dismantlers (automotive recyclers are working on standards and codes of practice to address this issue).

- Ban the shredding of mercury switches from new vehicles, which could be achieved by discontinuing their use or requiring their removal prior to shredding.

- Adopt European Union targets for encouraging the reduction in the landfill disposal of ASR: 15% landfill for all vehicles by the year 2002, 10% landfill for new vehicles by the year 2002, and 5% landfill by the year 2015. This would support current initiatives by the Vehicle Recycling Partnership.

A More Comprehensive Environmental Policy

Policy-makers have a responsibility to develop clear priorities and targets for reducing environmental burdens and impacts. Well-defined, clear national policies are valuable in guiding corporate management in setting policies and directives for products and processes. The United States lacks a comprehensive environmental management policy that addresses energy use, pollutant emissions, and hazardous waste. National policies on energy, wastes, and greenhouse and other pollutant emissions do not include specific targets and goals to guide improvement. The EPA has prioritized risks to human and ecological health in the Relative Risk Reduction Project,[30] which can provide some guidance on weighing impacts categories. Major environmental problems were identified and categorized into high, medium, and low risks, but specific targets for reducing these risks have not been established. These specific targets would help OEMs set priorities for addressing tradeoffs that exist in evaluating the life cycle impacts associated with future alternative designs.

8.2.3 Manufacturers

The automotive industry is faced with many challenges that can be linked to performance, cost, environmental, and legal requirements for the automobile, which often conflict. Interior space, comfort, acceleration, manufacturing costs, fuel economy, safety, material intensity, recyclability, and emissions currently are some of the key requirements that shape the design of the automobile. This complexity of requirements that influences the life cycle of the automobile demonstrates the need for a comprehensive framework and tools for design and management. Multicriteria matrices presented in Chapter 2 enable stakeholders to identify and evaluate these requirements. Without explicit specification of the performance, cost, environmental, and legal requirements for the vehicle life cycle system, improvement strategies likely will address discrete issues rather than optimizing the total vehicle life cycle. Ingenuity and capability exist in the industry, but accelerating the rate of progress toward more sustainable automobiles will require special leadership. Life cycle design and management represents a new paradigm for OEM responsibility in the development of new vehicles.

Improvements can be made incrementally or through more radical innovations that incorporate leapfrog technologies. Analysis of innovative technologies within the current design paradigm for the automobile often will lead to their rejection because of conflicts with existing requirements of the current vehicle design. In this case, innovative solutions become stifled. Although many opportunities exist for incremental improvement of conventional vehicles, this section emphasizes more innovative changes in vehicle design.

Analysis of design opportunities for improving the automobile life cycle have led to the following key findings and recommendations.

Alternative Vehicles

The PNGV has set a goal of 80 mpg of gasoline or equivalent (114,132 Btu). This program is a partnership between the federal government and USCAR, which includes Chrysler, Ford, and General Motors. PNGV supports a range of research and development areas applicable to alternative vehicles.

Battery-Powered Electric Vehicles

From a life cycle perspective, battery-powered electric vehicles (EVs) do not appear to offer significant environmental advantages over internal combustion engine vehicles (ICEVs). A study being conducted by DOE should provide a more definitive comparison of both systems. At this time, the following arguments for and against EVs can be made:

- Mobile pollutant emissions from vehicle operation during the use phase are virtually eliminated. Contrary to popular understanding of the EV, this system is not clean. In particular, significant emissions from fossil-fuel-burning power plants are associated with battery recharging. In addition, ecological consequences arise from hydroelectric power, and long-term risks are posed from processing uranium for nuclear power and storage of the spent fuel.
- Comparative assessments of life cycle emissions, based on the national grid for electricity production, indicate that CO and HC emissions are reduced relative to ICEVs; SO_2 and particulates are higher. Higher SO_2 and particulate emissions result from electricity production from coal, which accounts for 56% of the total electricity generated for the U.S. grid. Greenhouse gas emissions in CO_2 equivalents were found to be 5% higher for EVs compared to ICEVs. However, emissions from EVs vary dramatically, depending on the energy source for electricity production.
- Investigations of life cycle energy consumption for ICEVs and EVs do not consistently show a clear advantage of one propulsion system over the other. Sullivan and Hu[15] showed that an EV had a 25% lower life cycle energy compared to a functionally equivalent ICEV. An earlier study by Wang and DeLuchi[31] analyzed ICEV and EV energy consumption using four primary energy sources: petroleum, natural gas, biomass, and coal. They calculated the energy consumed in the production of gasoline from biomass and coal, in addition to a petroleum feedstock. Two scenarios were studied based on 1995 and the year 2010 conditions. They found that 1995 EVs required 8 to 30% more energy relative to the petroleum-powered ICEV when coal, petroleum, or natural gas (NG) is used as the primary energy source for electricity. For the year 2010 scenario, which assumed improvements in EV design and power plant conversion efficiencies, EVs would reduce their relative primary

energy consumption by 7 to 20% if the primary source for electricity production is petroleum, 15 to 27% for natural gas, and 17 to 29% for coal. Electric vehicles operating on electricity produced by biomass would increase primary energy consumption by 6 to 23%.
- Electric vehicles powered by most battery types currently have a limited driving range relative to ICEVs, which is substantially reduced by heating and cooling loads. Current EVs typically have a range less than 100 miles. However, a range of 238 miles recently was reported for the GM Ovanic LLC, an EV powered by a nickel metal hybrid battery.[32]
- Disposition of batteries was reviewed recently by Gaines and Singh.[33] They concluded that no major technical or institutional barriers caused by production and recycling of battery materials exist which would prevent the introduction of EVs on a large scale.

Hybrid Drives

Hybrid drives combine two different drive components in a way that maximizes the advantages of each under varying road load conditions, thus achieving performance benefits that may justify the increased production costs. The typical storage devices for hybrid drives are ultracapacitors, flywheels, and batteries. These storage devices are used to recapture energy during braking and to generate additional power during peak power requirements such as climbing hills and rapid acceleration. The hybrid drive system, which combines an internal combustion engine and electric drive, has the near-term potential of being an alternative to conventional gasoline-driven automobiles for the following reasons:

- The current internal combustion engine drive does not efficiently match the road load requirements under all driving conditions. This leads to a drop in efficiency at part load, which also influences emissions. In a hybrid drive system, the internal combustion engine can operate in its maximum efficiency regime, whereas the alternative electric or flywheel drive can operate efficiently during partial load.
- Fuel economy for a state-of-the-art series hybrid vehicle over the Federal Urban Driving Schedule and Federal Highway cycles was found to be greater than a conventional ICEV.[34] However, a life cycle comparison of the hybrids and conventional vehicle has not been performed.

The internal combustion engine and the electric drive can be arranged in series or in parallel. Although the series configuration is mechanically simpler, the parallel configuration offers greater performance flexibility through greater reliance on the internal combustion engine.[35] However, greater reliance on internal combustion may result in lower fuel economy and higher emissions.

Hypercars

The hypercar proposed by Lovins[36,37] represents one of the most innovative concepts for achieving ecologically and economically sustainable automobiles. The combination of ultralight and hybrid vehicle technologies offers tremendous advantages through design synergy. Lovins *et al.*[37] project that their preliminary design and plan for the hypercar would achieve the following:

- Hypercars would weigh three- to fourfold less than today's steel production cars.
- A fuel efficiency increase of five- to twenty-fold is expected.
- The number of parts for the proposed design would be reduced dramatically.

These overwhelming and apparent advantages indicate that a prototype should be built and tested. Several issues that should be addressed during prototype development include the following:

- The propulsion system of the hypercar would not generate the same magnitude of waste heat; therefore, heating the cabin would require additional energy inputs or a better insulated cabin which significantly reduces heat loss.
- A strategy for end-of-life management of the 207 kg of plastic and composite parts and components for the proposed 1998 design should be further developed. However, without recycling, ASR from the hypercar would be of the same magnitude as ASR from a conventional vehicle.
- Issues of road stability and safety must be researched through prototype testing. Road stability and traction in winter weather could pose challenges to the hypercar design.

Alternative Materials

Material selection for the automobile has been driven primarily by performance and cost requirements. Weight (fuel economy contribution), toxicity, and recyclability also are important environmental criteria that have influenced material selection decisions. While strong competition exists among alternative automotive materials, no single material is expected to meet the full spectrum of design requirements for all applications. Lightweight materials clearly will be necessary to achieve significant improvements in fuel economy. Tradeoffs for lightweight materials exist with respect to energy consumption and emissions associated with material production, durability and useful life, and end-of-life management. Life cycle assessment has not been used extensively for evaluation of alternative automotive materials, but many studies have recently been conducted or are now underway. Specific recommendations regarding material selection include the following:

- Eliminate the use of mercury in switches unless the switches can be easily disassembled prior to shredding; OEMs have committed to eliminating mercury wherever possible.

- The current disposal of plastics in ASR represents a significant loss of valuable energy/material resources. Although plastics may offer important advantages in manufacturability, lightweighting, and performance, efforts should be expedited in design for x where x = remanufacturability, reuse, recycle, energy recovery, and development of new processes to facilitate end-of-life management of plastics.

- Guidelines and checklists for life cycle design should be made available to design engineers at OEMs and suppliers. The OEMs have developed lists of materials of concern and design guidelines on material selection.

- Opportunities to use secondary materials that meet essential performance criteria should be encouraged.

Alternative Fuels

Although diesel and reformulated gasoline are not alternative fuels as defined by EPA, they are included in this discussion. Many fuel properties and combustion characteristics of alternative fuels must be considered when designing engines and fuel systems. A comprehensive assessment of the environmental impacts across the full fuel cycle is not available. However, some preliminary comparison of the different fuels can be made on the basis of greenhouse gas emissions, energy density, practicality for onboard use, and cost.

Life cycle greenhouse gas emissions of alternative fuels (materials production, vehicle assembly, vehicle operation, and fuel production) was studied by DeLuchi.[17] As shown in Table 5.20 in Chapter 5, the lowest greenhouse gas emissions are associated with solar-powered EVs and ICEVs powered by hydrogen produced from photovoltaics. Although greenhouse gas emissions are low for liquid hydrogen produced from solar power, they are 1.35 times that of an EV operating on electricity provided by photovoltaics. At present, reformulated gasoline and diesel are more feasible fuel sources, as are alternatives such as liquefied petroleum gas (LPG, propane), natural gas, ethanol (corn is the most likely source in the United States), methanol (now generally produced from natural gas), and electricity from the current U.S. grid. Among these fuels, LPG vehicles have the lowest greenhouse gas emissions (378 g/mi), followed by natural gas (423 g/mi) and diesel (424 g/mi). Vehicles using ethanol from corn have the highest emissions among the most feasible fuels with 588 g/mi. ICEVs powered by methanol produced from coal would emit CO_2 equivalents of 798 g/mi.

The energy density (MJ/l) of liquid fuels helps determine the practical driving range of alternative fuels. Diesel has an energy density 1.15 times that of gasoline; liquid hydrogen and LPG have densities approximately 0.75 times that of gasoline. Ethanol (with an energy density 0.65 that of gasoline) and methanol (with 0.5 the energy density of gasoline) may produce some range problems with conventionally sized fuel tanks. Compressed natural gas has a much lower energy density and thus may result in vehicles with limited range. Liquefied natural gas and liquefied hydrogen present substantial problems for onboard fuel systems. Because of vessel size and weight, possible leakage and hazards, and the need for extremely low temperatures, neither of these fuels seems practical at present.

The cost of CNG, diesel, and methanol are similar to gasoline on an equivalent energy basis. LPG, ethanol, and liquid hydrogen range from moderately to substantially more expensive.

Considering greenhouse gas emissions, onboard performance, and cost, it appears that diesel and LPG may provide some modest advantages over gasoline. In terms of greenhouse gas emissions and costs, CNG has a slight advantage over gasoline but a lower energy density and significant storage problems. Other alternative fuels are either impractical or do not provide significant improvements over gasoline at present. In the future, some alternative fuels may emerge in other applications, such as fuel cells. More comprehensive information on pollutant emissions could change this analysis.

Emissions Control

For conventional vehicles, various opportunities and challenges exist for reducing use phase emissions. The following items address emissions control:

- The major difficulty in vehicle emissions control is that the HC and CO emission requirements often are opposite to NO_x emission requirements. Emissions of CO, HC, and NO_x are distributed differently between stabilized running, cold/hot start, and high-power operation during the driving cycle. Some technologies for emissions control are stratified charge, lean-burn technology, and catalyst control. However, the major hurdle is to design an emissions control system that simultaneously reduces all tailpipe emissions (HC, CO, and NO_x) and evaporative emissions.
- Emissions control technology is associated with increased cost. This results in a tradeoff between environmental and cost criteria. The consumer currently is not willing to pay more for a cleaner vehicle.[38]
- With the same type of engine design, calibration, and catalyst position, it is more difficult to meet emission requirements and preserve high fuel economy as the vehicle size and weight increase and as the engine size increases to maintain constant performance. With some exceptions, a small engine in a small vehicle has high fuel economy and low emissions.
- An increase in fuel economy through engine parameter control such as spark timing and compression ratio increase may result in an increase in emissions. For example, for the same catalyst efficiency, spark retard for partial NO_x and HC control results in decreased fuel economy.
- The use of alternative fuels shows the potential for reducing emissions. A large-scale use of alternative fuel will reduce the production cost of these fuels.
- Approximately 40 to 50% of tailpipe emissions are caused by deterioration or malfunctioning of the vehicle emissions control system.[16] Because most on-road emissions result from a small number of high-emitter vehicles, an effective inspection/maintenance (I/M) program can substantially reduce vehicle emissions.

Manufacturing

Successful pilot pollution prevention projects that have been implemented by OEMs to reduce environmental impacts in manufacturing should be transferred to other plants and facilities. The OEMs have demonstrated the potential for reducing environmental burdens in manufacturing, particularly in relation to chemicals management, toxic chemicals substitution, and packaging waste reduction. Programs to eliminate waste at assembly plants should continue to be promoted. Paint-related solvent emissions remain a key challenge for the industry.

Management

The OEMs have published environmental reports outlining their environmental management systems and progress toward reducing environmental impacts. In addition, specific guidelines and directives are being developed to support implementation of environmental policies. However, the effective application of life cycle design tools will be limited by the user's ability to make tradeoffs between the diverse set of environmental impacts such as global warming, ozone depletion, energy consumption, solid waste, and various other impact categories. Environmental management systems currently lack specific targets and goals to assist in the prioritization and weighting of impacts. Corporations must establish their own policies, and/or the government must provide national policies, to effectively guide improvement.

Life Cycle Assessment Tools

Life cycle assessment tools such as inventory analysis cannot be used yet on a routine basis in the design of automotive parts and components. Databases are not yet mature enough to support analyses of the diversity of materials and processes used in automobile manufacturing. However, life cycle assessment can be used as a planning tool to evaluate alternative designs and to identify areas for improvement. Numerous life cycle assessment and design research initiatives have demonstrated the capability of life cycle assessment in computing the total environmental burden related to alternative designs and in clarifying the tradeoffs that exist between them. It is becoming apparent that these tools are essential for evaluating the complexity of environmental issues that encompass automotive design.

8.2.4 Final Remarks

The Current Conventional Automobile: Sustainable?

In light of the guidelines for sustainability previously discussed, the current conventional automobile does not appear to be a sustainable mode for transportation in an expanding global marketplace. The automobile life cycle is highly resource intensive, generates significant releases of environmental pollutants, and is one of the primary contributors to greenhouse gas emissions. During the 1900s, the automobile has undergone substantial change that has emphasized improvement in performance. Speed, comfort, safety, reliability, and handling are some of these performance factors. At the same time, major reductions in environmental burdens across the life cycle of the automobile also have been achieved by OEMs. These achievements demonstrate OEMs' ability to combine technology and innovation to address complex problems.

However, the tremendous growth in automobile use now threatens the global environment. The realization of more sustainable automobile systems will require significant changes to government policy, user behavior, and vehicle design practices.

Understanding the key environmental impacts of the automobile life cycle and opportunities for improvement should provide a basis to achieve sustainable transportation systems. In particular, more efficient public transportation, such as buses and rail, should be encouraged as major complements to the automobile.

Multiple Stakeholders: Impact of Decisions on Automobile Life Cycle

Decisions made by many stakeholders, such as suppliers, OEMs, users, end-of-life vehicle managers, regulators, insurers, and educators, determine the life cycle environmental profile for each automobile. Decisions that affect the future direction of the automobile are guided by a large set of variables and parameters either explicitly specified or loosely defined by these stakeholders. The market and demand for new vehicles and driving behavior and maintenance practices are among the primary factors determined by owners and users. In the United States, increased market demand for light-duty trucks that are less fuel efficient than passenger vehicles is an important trend that should be reversed to reduce the environmental impacts of the automobile. Manufacturers translate consumer needs and perceived needs into designs that ultimately shape the environmental profile of the automobile life cycle. For example, practical limits to fuel economy, emissions factors, material intensity, and feasible options for vehicle retirement are set by the design. Regulators and policy-makers will control the life cycle system in the broadest sense by setting limits and standards and by creating incentives and disincentives for design and management of the automobile life cycle.

The total environmental impact of the automobile is primarily a function of the design of the fleet of vehicles on the road and VMT. Alternative vehicles that represent a more ecoefficient design will not lead to a reduction in total environmental impact if total VMT increases dramatically.

New Requirements Needed

This book has identified many actions that can be taken by the primary stakeholders to improve the automobile life cycle. The automobile system can be characterized as a set of performance, cost, environmental, and legal requirements that are determined by stakeholders. Improvements can be made within the existing set of requirements or through their modification. These requirements conflict, and their intersection often leads to narrowly defined opportunities for change. Incremental environmental improvement based on existing requirements will not keep pace with projected growth in demand and will not adequately address the magnitude of the environmental impacts. Therefore, fundamental changes in automobile design are necessary to ensure that major environmental consequences on a global scale are avoided. Such fundamental changes can be achieved only by revising and specifying new requirements for the automobile life cycle.

Improvement Opportunities: Rank by Potential for Change

A hierarchy of improvement opportunities can be established based on their potential for change.

Dramatic changes lie at the highest level. These changes include programs such as alternative vehicles, advanced materials, regulatory reform to facilitate life cycle design, economic instruments such as energy taxes, a well-defined national environmental policy with goals and targets, and urban planning to reconstruct driving patterns. At the other end of the spectrum stand strategies for improving conventional vehicles. These actions may address only discrete life cycle stages or processes that do not affect other parts of the life cycle (i.e., reducing packaging wastes in manufacturing).

Significant Changes in Design, Management, and Policy: Needed for Sustainable Automobiles

Successfully guiding automobile systems toward sustainability may require a tightening of the environmental requirements, but certain performance requirements may be compromised. For example, maximum speed and acceleration, vehicle size, range, and convenience are examples of performance requirements that can be modified to enable alternative designs that may be significantly more sustainable. Innovative technology already exists and has been demonstrated in a variety of concept cars, but these have not been launched because of performance or cost issues. The PNGV and the hypercar proposed by Lovins *et al.*[37] are alternative vehicle initiatives that are seeking not to compromise performance and cost requirements. Clearly, tools and metrics for evaluating improvements may require modification to achieve goals for sustainability. Change in such a large and complex system often is stifled by existing capital investment, experience, bureaucracy, and behavior. The creative processes of engineers and designers often are restricted by a rigid set of requirements and conditions. Pricing of energy, corporate accounting systems, employee merit evaluations, and advertising campaigns will require reform to shift the dominant paradigm. This can be achieved only if some recognition develops that the automobile represents a serious environmental problem. Rapid change in conventional vehicle design can be catastrophic; phasing in change based on well-planned and well-communicated programs is necessary for success.

Life Cycle Framework: Basis for Effective Partnerships

The life cycle system provides a logical framework for design and management toward more sustainable transportation systems. Partnership approaches based on this framework have the potential to accelerate change, compared to stakeholders acting independently. These approaches are necessary to overcome the barriers and conflicts that exist among stakeholders and their special interests.

Automobile ownership and use is a privilege. The extent to which society fully recognizes the environmental and social consequences associated with automobiles will determine when significant opportunities for improvement will be effectively realized.

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Appendix 1

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Appendix 2

Definitions of Industrial Ecology

Allenby, B.R., "Achieving Sustainable Development through Industrial Ecology," *International Environmental Affairs*, Vol. 4, No. 1, pp. 56–68, 1992.

Somewhat teleologically, "industrial ecology" may be defined as the means by which a state of sustainable development is approached and maintained. It consists of a systems view of human economic activity and its interrelationship with fundamental biological, chemical, and physical systems with the goal of establishing and maintaining the human species at levels that can be sustained indefinitely, given continued economic, cultural, and technological evolution.

Jelinski, L.W., Graedel, T.E., Laudise, R.A., McCall, D.W., and Patel, C.K.N., "Industrial Ecology: Concepts and Approaches," *Proceedings of the National Academy of Sciences USA*, Vol. 89, pp. 793–797, 1992.

Industrial ecology is a new approach to the industrial design of products and processes and the implementation of sustainable manufacturing strategies. It is a concept in which an industrial system is viewed not in isolation from its surrounding systems but in concert with them. Industrial ecology seeks to optimize the total materials cycle from virgin material to finished material to component, to product, to waste products, and to ultimate disposal. Characteristics include:

1) Proactive, not reactive
2) Designed in, not added-on
3) Flexible, not rigid
4) Encompassing, not insular

Patel, C. and Kumar, N., "Industrial Ecology," *Proceedings of the National Academy of Sciences USA*, Vol. 89, pp. 798–799, 1992.

Industrial ecology can be best defined as the totality or the pattern of relationships between various industrial activities, their products, and the environment. Traditional ecological activities have focused on two time aspects of interactions between the industrial activities and the environment—the past and the present. Industrial ecology, a systems view of the environment, pertains to the future.

Lowe, E., "Industrial Ecology—An Organizing Framework for Environmental Management," *Total Quality Environmental Management*, Autumn, pp. 73–85, 1993.

The heart of industrial ecology is a simple recognition that manufacturing and service systems are in fact natural systems, intimately connected to their local and regional ecosystems and the global biosphere The ultimate goal of industrial ecology is bringing the industrial system as close as possible to being a closed-loop system, with near complete recycling of all materials.

Tibbs, H.B.C., "Industrial Ecology: An Environmental Agenda for Industry," *Whole Earth Review*, Vol. 77, pp. 4-19, 1992.

Industrial ecology involves designing industrial infrastructures as if they were a series of interlocking manmade ecosystems interfacing with the natural global ecosystem. Industrial ecology takes the pattern of the natural environment as a model for solving environmental problems, creating a new paradigm for the industrial system in the process.

The aim of industrial ecology is to interpret and adapt an understanding of the natural system and apply it to the design of the manmade system, in order to achieve a pattern of industrialization that is not only more efficient, but that

is intrinsically adjusted to the tolerance and characteristics of the natural system. The emphasis is on forms of technology that work with natural systems, not against them.

Frosch, R.A. and Gallopoulos, N.E., "Strategies for Manufacturing," *Scientific American*, Vol. 261, No. 3, pp. 144–152, 1989.

The industrial ecosystem would function as an analog of biological ecosystems... An ideal industrial ecosystem may never be attained in practice, but both manufacturers and consumers must change their habits to approach it more closely if the industrialized world is to maintain its standard of living—and the developing nations are to raise theirs to a similar level—without adversely affecting the environment.

Graedel, T.E. and Allenby, B.R., *Industrial Ecology*, Prentice Hall, Englewood Cliffs, NJ, 1995.

Industrial ecology is the means by which humanity can deliberately and rationally approach and maintain a desirable carrying capacity, given continued economic, cultural, and technological evolution. The concept requires that an industrial system be viewed not in isolation from its surrounding systems, but in concert with them. It is a systems view in which one seeks to optimize the total materials cycle from virgin material, to finished material, to component, to product, to waste product, and to ultimate disposal. Factors to be optimized include resources, energy, and capital.

Hawken, P., *The Ecology of Commerce,* Harper Business, NY, 1993.

Industrial ecology provides for the first time a large-scale, integrated management tool that designs industrial infrastructures "as if they were a series of interlocking, artificial ecosystems interfacing with the natural global ecosystem." For the first time, industry is going beyond life-cycle analysis methodology and applying the concept of an ecosystem to the whole of an industrial operation, linking the "metabolism" of one company with that of another.

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f = figure; t = table