



THESIS



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TECHNOLOGICAL SUBOPTIMIZATION AND THE U.S.
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Louis Silvia, Jr.

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Louis Silvia, Jr.

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ABSTRACT

TECHNOLOGICAL SUBOPTIMIZATION AND THE U.S. AUTOMOBILE INDUSTRY

By

Louis Silvia, Jr.

The purpose of this dissertation is to contribute to the understanding of technological change. The study differs from the bulk of the investigations in this area in three ways. First, an industry study approach is used instead of a cross-sectional analysis. Second, the methodology is institutional rather than econometric. Third, the study is oriented towards market performance instead of conduct.

In the first part of the dissertation a theory of social optimality in the production and use of technology is developed. Three conditions must be met for a social optimum: technology production must be efficient; the rate of technology production must be such that net social benefits are maximized; and the existing stock of technology must be used in a way such that no other selection of currently available technology results in a greater sum of producer and consumer surpluses. Failure to meet these criteria is referred to, respectively, as Type I, Type II, and Type III suboptimization. The possibilities of technological suboptimization by the auto industry are then discussed.

In the last part of the thesis attention is focused on suboptimization in powerplant technology. The technology of alternative powerplants (Otto, stratified charge, Diesel, rotary, Rankine, gas turbine, Stirling, and electric) is examined with the use of corporate, government, and other reports. The industry's efforts to promote powerplant technology is also reviewed. The evidence was of little help in evaluating the extent of Type I suboptimization. The data strongly suggest, however, that Type II suboptimization was present. That is, given the technological opportunities in the powerplant field, it appears that the industry's efforts fell short of the socially desirable level. Finally, the evidence is ambiguous on Type III suboptimization; it is unclear that the industry's continued commitment to the conventional internal combustion engine during the mid-1970's conflicted with the social interest.

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TO MY PARENTS

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INTRODUCTION

In December 1978, the U.S. Secretary of Transportation, Brock Adams, addressed the Detroit Economic Club. Mr. Adams challenged the American automobile industry to reinvent the automobile. Refinement was not enough: nothing less than a "quantum jump" in engine technology was necessary to save the automobile's role in American life. Adams' challenge implied that the current state of domestic automotive research and development was not in line with the national interest.

Shortly after the speech, the largest and most profitable automaker, General Motors, stated that "the record of technological progress in the automobile industry is unparalleled, and American manufacturers remain preeminent in automotive technology;"¹ GM's defense of the industry was echoed by its fellow automakers.

Nevertheless, at a meeting with President Carter the following spring, the automakers agreed to join the federal government in sponsoring the development of a totally new car.² Given Congressional approval, much of the work will be done on university campuses.

These events raise a number of interesting questions:

- (1) Has technological progress in the U.S. auto industry been inadequate?
- (2) If so, what have been the causes?
- (3) If so, what are the public policy remedies?

This dissertation attempts to answer these questions. Since the controversy over the industry's progressiveness is largely centered on the car's powerplant, the study focuses on that area of automotive technology.

Before looking at the evidence on powerplant development, it is necessary to develop criteria of optimality in the production and use of technology and to identify factors which may prevent the satisfaction of these criteria. These are the goals of Chapter I.

In Chapter II, the structural and behavioral features of the market for automotive technology are analyzed. The likelihood of technological suboptimization in the automotive field is discussed.

The level of powerplant technology during the mid-1970s is examined in Chapter III. The merits of alternative powerplants are reviewed to determine whether the standard internal combustion engine has remained the best choice.

The rate of development of alternative powerplants is discussed in Chapter IV. Here, the crucial question is whether the observed rate of development approximates the socially optimal one.

In Chapter V, conclusions and their implications for public policy are presented. The contribution of the thesis to the understanding of technological change in general is then discussed. Finally, suggestions for further research are offered.

It is unlikely that this thesis will resolve the controversy over auto industry performance. The issues are complex, the data imperfect. Yet, if future discussions of this important industry are at least enlightened as a result of this study, it will have achieved its goal.

NOTES

1. The Detroit News, December 6, 1978.
2. Ibid., May 19, 1979.

CHAPTER I

SUBOPTIMIZATION IN THE PRODUCTION AND USE OF TECHNOLOGY

1. Invention and Innovation

Professor Schumpeter defined invention as the creation of "new possibilities."¹ One possibility is the reduction of a good's cost of production. Another is the making of better goods. An increase in society's stock of technology is required for these possibilities to come about. Invention, therefore, can be viewed as the production of technology. This is a broad use of the term, for it includes everything from the explorations of basic research to the last steps of development.

Invention is a process of experimentation and observation. Like other production processes, invention consumes labor services, capital, and natural resources. However, the production function for invention is difficult to formulate.² It is hard to quantify the output in a

practical way; equally troublesome is the measurement of that peculiar input called creative insight.

But even if the measurement problems could be solved, another difficulty remains. Simply not enough is known about the production of creative insight itself. Unlike the other inputs to the production of technology, creative insight seems to materialize out of thin air. More important, its occurrence cannot be regulated by the inventor.

Thus the production function for invention is a probabilistic relation. Unlike the usual concept of the production function, which asserts a fixed relation between inputs and output, invention is a process where, for any given sacrifice of tangible inputs, a range of output levels is possible. The extent of creative insight determines the actual outcome.

The use of new technology is called innovation. Professor Schumpeter defined it as "'doing things differently' in the realm of economic life."³ Process innovation refers to an advance in production techniques, while product innovation is the making available of new goods.

2. Optimization in the Production and Use of Technology

The optimal conditions for the production and use of new technology are now set forth.⁴ The analysis is restricted to the invention and innovation of new goods.

Assume a prodigiously enlightened society. This society can measure, with certainty, the benefits and costs of invention and innovation throughout time. Further

assume that technology is quantifiable in units called "techtils." New products are distinguished by the embodiment of some number of formerly non-existent, or unutilized, techtils: to simplify further, assume that this number always equals one.

At $t=0$ society determines the optimal rate of technology production. This calculation requires a weighing of the benefits and costs of the production and use of each unit of new technology.

First consider the cost of producing a new unit of technology. The development time for a new techtil may be varied according to the commitment of resources per unit time to invention. Let $C(T)$ denote the monetary value at time $t=0$ of the cost stream required to produce a techtil by time T .

Furthermore assume that

$$(1) \ C(T) > 0, \ C'(T) < 0, \ C''(T) > 0 \text{ for all } T > 0.$$

Crash programs are assumed to be more expensive than leisurely ones. Conversely, if the unit is not produced ($T \rightarrow \infty$), $C(T)$ is equal to zero.

The monetary flow of the social cost of producing the innovation is given by $K(t,q)$, where q is the rate of production of the new product at time t . Assume

$$(2) \ K(t,0) = 0, \ \frac{\partial K}{\partial q} > 0, \ \frac{\partial^2 K}{\partial q^2} > 0, \ \frac{\partial K}{\partial t} \leq 0.$$

The cost of innovation is zero if there is no production. The marginal cost of production is positive and increases with output. A product's cost of production may change

over time due to changes in input prices.

Invention itself is assumed to provide no benefits. Instead, social benefits are derived solely from the consumption of goods. Thus the benefits of new technology are realized only after innovation. The monetary flow of social benefits at time t of a new product is given by $B(t,q)$, where q is the rate of consumption (and production) of the new product at time t . Assume that

$$(3) \quad B(t,0) = 0, \quad \frac{\partial B}{\partial q} > 0, \quad \frac{\partial^2 B}{\partial q^2} < 0, \quad \frac{\partial B}{\partial t} \lesseqgtr 0.$$

The marginal social benefits of a new product decline with increases in consumption. Changes in preferences or subsequent innovations may cause the flow of benefits to fluctuate over time.

Now let V denote the present net monetary value of a new product at time $t=0$ where

$$(4) \quad V = \int_0^\infty B(t,q)e^{-rt} dt - \int_0^\infty K(t,q)e^{-rt} dt - C(T).$$

Thus benefits and costs are assumed to be continuously discounted at rate r .

The value of V depends on the length of the development period, T , and the rates of production after innovation. The maximization of V requires satisfaction of the following first order conditions:

$$(5) \quad \frac{\partial V}{\partial T} = -B(T,q)e^{-rt} + K(T,q)e^{-rt} - C'(T) = 0$$

$$(6) \quad \frac{\partial V}{\partial q} = \int_0^\infty \frac{\partial B}{\partial q} e^{-rt} dt - \int_0^\infty \frac{\partial K}{\partial q} e^{-rt} dt = 0.$$

Equation Five states that the period of development should be such that the discounted marginal social benefits of shortening the period equals the discounted marginal social costs. Equation Six states that once invention is complete, innovation should take place immediately. The production of the new product is set at a rate where the discounted marginal social benefits equal the discounted marginal social costs of production.

Solution of Equations Five and Six gives an optimal period of development, T^* , for a new unit of technology, and the optimal rate of production over time of the resulting new product. Substitution of these values into Equation Four gives the maximum value of V at $t=0$.

If the maximum present net value of a new product is greater than zero, it is worthwhile for society to invent and innovate. If the same procedure is followed for all possible new products whose present net value is greater than zero, society is optimizing in the production and use of new technology.

3. Three Kinds of Suboptimization in the Production and Use of Technology

Three kinds of suboptimization in the production and use of new technology can be defined. These are called Type I, Type II, and Type III suboptimization.

Type I suboptimization is the inefficient production of technology. For some reason, the cost of producing units of technology tends to be greater than the achievable

minimum. If such inefficiency exists, the effect is to reduce the present net value of potential products. As a result, the production of new technology would tend to fall short of the socially optimal rate.

Type II suboptimization is the production of new technology at a rate greater or less than the socially optimal rate. This kind of suboptimization may exist even if the production of technology is efficient. In this case, society does not properly take into account at least one of the flows represented by $B(t,q)$, $K(t,q)$, or $C(T)$. Consequently, there may be either too much or too little in the way of innovation.

Type III suboptimization is the neglect of already produced technology which, if embodied in some new product, would increase social welfare. Under the ideal conditions described in section two, Type III suboptimization is non-existent, since a smooth dovetailing of invention and innovation always occurs. Type III suboptimization, therefore, refers to a break in the transition from invention to innovation.

4. Technological Suboptimization in a Market System

Unlike the markets for most physical outputs, the markets for new technology are not highly visible. A number of things are responsible for the obscurity of technology markets. First, it is difficult, if not impossible, to count units of technology in any practical way. Secondly, the output of new technology does not

stand alone. Rather, it is embodied in firms' physical outputs. Third, even with a patent system, the establishment of property rights may be uncertain. Finally, firms often produce their own technology and subsequently use it. This kind of vertical integration may be extensive enough to internalize a technology market completely, or nearly so, within firms.

Despite these complications, the production of technology can be usefully analyzed with the market model. Since technology is a resource, its demand is derived from an end-use. Thus there exists a demand for steel-producing technology, aerospace technology, or automotive technology. Firms are on the supply side of technology markets. The technology-producer may be a private inventor, an engineering consulting outfit, or the giant corporation's research and development department. The interaction of the demand for new technology and its supply determine the rate of technology-production.

Type I suboptimization is technical inefficiency in the supply of new technology.⁵ Technology producers may be operating at too small or too large a scale of plant. Or, there may be X-inefficiency, where, at a given scale, resources are either poorly organized or are not fully utilized.⁶ A necessary cause of Type I suboptimization is the same as that of technical inefficiency in general, viz., insufficiently vigorous competition that allows the non-minimization of costs.

Type II suboptimization refers to a market rate of output which is not allocatively efficient.⁷ A number of factors may cause Type II suboptimization. First, there may be externalities which create a divergence between private and social benefits and/or private and social costs of technology production and use. Second, monopolistic elements at the level of the end-use market may affect the demand for new technology in a socially undesirable way. Third, market power at the level of technology production itself may result in an allocatively inefficient restriction of output. Market power on the side of the buyers of new technology is a fourth possible cause of Type II suboptimization. Differences in private and social discounting of the future benefits and costs of new technology is a fifth possible cause. Sixth, and finally, uncertainty about the benefits and costs of technology production may cause Type II suboptimization. To be sure, uncertainty in the real world is unavoidable. Within this constraint, uncertainty causes Type II suboptimization when the private and social aversities toward risk are different.

Unlike Types I and II, Type III suboptimization does not refer to poor performance in a technology market. Rather, it refers to poor performance in an end-use market. Type III suboptimization occurs with the neglect of innovation which would increase either producer or consumer surpluses at the end-use level. One possible cause of Type III suboptimization is the failure of information to flow from inventors to potential innovators. Second,

potential innovators may be slow to respond to new possibilities due to bureaucratic inertia. Third, a cartel-like agreement may discourage a firm from serious innovation. Serious innovation may be perceived as cheating and would invite the type of retaliation and vigorous competition that collusive firms wish to avoid.

NOTES

1. Joseph A. Schumpeter, Business Cycles (New York and London: McGraw-Hill, 1939), pp. 8-9.
2. On the concept of the production function see C. E. Ferguson, The Neoclassical Theory of Production and Distribution (London and New York: Cambridge University Press, 1969).
3. Schumpeter, op. cit., pp. 84-85.
4. This section follows the approach of M. I. Kamien and N. L. Schwartz, "Timing of Innovations under Rivalry," Econometrica 40 (January 1972): 43-60.
5. On the concept of technical efficiency see Douglas Needham, The Economics of Industrial Structure Conduct and Performance (New York: St. Martin's Press, 1978), pp. 231-232; and Joe S. Bain, Industrial Organization (New York: Wiley, 1959), pp. 352-354.
6. Professor Leibenstein is credited with identifying this form of economic inefficiency. See "Allocative Efficiency vs. 'X-Efficiency'," American Economic Review 56 (June 1966): 392-415.
7. On the concept of allocative efficiency see the following: William J. Baumol, Economic Theory and Operations Analysis, 3rd ed. (Englewood, NJ: Prentice-Hall, 1972); F. Bator, "The Simple Analytics of Welfare Maximization," American Economic Review 47 (March 1957): 22-59; Tibor Scitovsky, Welfare and Competition (Homewood, IL: Irwin, 1951).

In a proper consideration of allocative efficiency all markets are assumed to be perfectly competitive. In an economy where some markets are imperfect, however, optimal resource allocation in the remaining markets may not be given by marginal cost pricing. This is the problem of the second-best. Here the seminal work is R. G. Lipsey and K. Lancaster, "The General Theory of the Second Best," Review of Economic Studies 24 (December 1956): 11-32.

The theory of the second best is intractable when applied to real-world problems of resource allocation. For a practical guide, a third-best policy has been articulated by Professor Scherer. "Weighing the possible gains from success in approximating a second-best solution against the risks of overshooting the desired degree of monopoly," he writes, "I am inclined to believe that society will find itself in a superior

third-best position on the average under a generally procompetitive policy. See his Industrial Market Structure and Economic Performance, 4th ed. (Chicago: Rand McNally, 1973), p. 26.

This thesis assumes that Professor Scherer is correct and thus the general equilibrium implications of allocative efficiency are ignored.

CHAPTER II

THE MARKET FOR AUTOMOTIVE TECHNOLOGY

1. Introduction

The purposes of this chapter are (1) to present the institutional features of the automotive technology market, (2) to analyze this market theoretically and (3) to suggest the possibilities for technological suboptimization by this market.

Automotive technology is defined as the knowledge relevant to the design and production of automobiles. The measurement of technology, even in principle, presents difficulties. Even a single category of technology, such as automotive technology, is not homogeneous. For instance, one may speak of automotive technology relating to the powerplant, to the transmission, to techniques of production, etc., or according to some other system of classification. Technological change proceeds at different rates and in different directions. Thus the pace of technological

change can be expressed as a vector of an unspecified number of dimensions. In the next two chapters, the analysis will be restricted to technology production and use in the direction of powerplants.

As for the rate of change in a given direction, it is assumed that there exists a unit of technology which is called the "techtil." As in the case of the imaginary "util" of utility theory, the analysis does not require that the unit be measurable. Radical inventions and innovations are distinguished from refinement-type inventions and innovations in that the former embody more techtils.

2. The Institutional Setting

a. The Process of Invention in the Automotive Field

The process of invention can be broken down into a number of phases. The first phase is called "basic research." This has been defined as "the pursuit of knowledge for its own sake."¹ Basic research is concerned with the formulation and testing of scientific theories and hypotheses. It is, by definition, indifferent to the potential economic value of the new knowledge.

In the next phase of the invention process, applied research, the potential economic value of new knowledge is recognized. Applied research, like basic research, "is systematic, intensive study directed toward fuller knowledge of a given subject. However, it differs from basic research in that it seeks to show or indicate the means by which a recognized need may be met."² Examples of applied research

in the automotive field are studies in the chemistry of fuels and the search for corrosion-resistant materials.

Development follows research as the next major step in the invention process. While applied research is concerned with "what potentially valuable knowledge can be produced," development involves the uses of new knowledge. As the National Science Foundation has stated, "In development the findings are directed toward production of useful materials, devices, systems, or methods; this work includes design and improvements of prototypes and processes."³

In the first phase of development, exploratory development, the first prototypes are built. Prototypes are rudimentary configurations of potential innovations; the object is to see if a concept shows promise if embodied in some rough draft design. At this point, there is apt to be little or no concern with production costs.

The next phase is called advanced development: "Several design options may be available as solutions to particular component problems, but there are by definition no unsolvable technical problems remaining by this time."⁴ More refined prototypes are built in order to perfect the design configuration. Attention is given to integrating the potential innovation with existing automotive components, and preliminary estimates of production costs are made. Upon completion of advanced development, a final pre-production prototype is designed, and several are integrated into an automobile. This prototype represents

the best technical configuration that embodies the new concept.

The last major step in the invention process is called production engineering, or the manufacturing program. The goal of production engineering is the discovery of the best design configuration subject to cost targets. In most cases the best technical design is not the cheapest to build. More prototypes, called production prototypes, are built with changes that cut cost without seriously affecting the technical desiderata of the configuration. During this period there is extensive testing to locate "bugs" that might later bedevil consumers. If all goes well, invention is over and the design configuration is frozen.

Progress has never manifested itself in totally revamped autos. It generally takes the form of improvements in the various systems (powerplant, braking, steering, etc.) and individual parts of the car. Improvements in some components in one year are followed by improvements in others the next; for this reason, progress in the automotive field has often been called evolutionary instead of revolutionary.

Moreover, progress in particular systems or components has seldom taken the form of a sudden replacement of one design configuration by another. Rather, there is apt to be a prolonged struggle between rival design configurations for dominance in the marketplace.

The early development of clutches provides a good example. During the industry's earliest years, cars were equipped with cone friction clutches. Another design configuration, the multiple disc clutch, was introduced in 1909 and for some years was fairly popular with automotive engineers. A third design was eventually improved and came to displace both the cone and multiple disc types, however:

What finally proved the most successful clutch for automotive applications is the single-plate or single disc type. This is by no means a recent conception or invention, for clutches falling under this heading were used in automotive practice as early as 1910. However, these early spring-plate clutches had no friction facings, their metal plates, made either of cast iron and bronze or of cast iron and steel, being in direct contact with each other. In some cases, even, the chief advantage offered by the single-plate principle, that of permitting a very light driven member, was completely ignored, the central disc was made the driving, and the two pressure plates (which of necessity had to be much heavier), the driven member. Gradually, however, the correct principles of design were recognized, and the single-plate clutch gained in popularity. In 1925, 60 percent of all American passenger car models were equipped with single-plate clutches, and in 1930, the percentage had risen to 81 percent.⁵

b. Producers of Automotive Technology

The producers of automotive technology fall into three categories. These are the vendors that supply the automakers with components and raw materials, "inventor-firms," and the automakers themselves.

Approximately 50,000 firms are vendors to the U.S. auto industry. These range from large firms such as U.S.

Steel, General Electric, and Eaton to really small ones which supply minor parts.

Automotive suppliers have been very important sources of invention.⁶ In 1958, George Romney, then president of American Motors, testified that "all companies in the automobile industry have the benefit of the vast research organizations of supplier industries and companies, and that area of research vastly outweighs the area of research and improvement that is occurring right in the motor-vehicle industry itself."⁷

The invention of automotive pollution control equipment exemplifies the continued importance of suppliers in recent years; a 1975 report of the Environmental Protection Agency pointed out the valuable contribution of suppliers:

When emission control devices became necessary the industry often looked to their suppliers not only for the actual production of the hardware but the design expertise as well. The best example of an emission control device that has been designed and developed outside the industry is the catalytic converter. Some domestic manufacturers have developed considerable capability in this area but the suppliers generally have more capability in the catalyst area than the automakers themselves

. . . The suppliers have a vested interest in the maintenance of the standards as they hope to sell the technology and hardware necessary to achieve compliance. The automakers, on the other hand, cannot "sell" the low emission characteristics of their cars to the average new car buyer. To an automaker the standards represent a cost that has little benefit, in our opinion. The emission control development approach by the suppliers has generally been more aggressive than that taken by the automakers.⁸

Traditionally, vendors have concentrated on the earlier phases of the invention process. In 1927, J. H. Hart, a top engineer of General Motors, wrote that "a great deal of important automotive engineering work is handled by the parts manufacturers, who have engineering staffs engaged not only in the parts they are manufacturing at the time but in developing parts and accessories for future products Work in the research department of such a company frequently is closer to fundamentals than at the car producing company."⁹ Similarly, Lawrence White, writing in the early 1970's, noted that "the auto companies have allowed their suppliers to take the risks and absorb the initial costs of developing new technology."¹⁰

The second class of automotive technology producers may be called "inventor-firms." This class is made up of individuals and firms that are not generally in contact with the automakers (or their vendors) on a regular basis.¹¹ Usually, these technology producers are more interested in securing the patent rights on a new idea while leaving production to others. Inventor-firms have made important contributions to the advancement of automotive technology. Examples include hydraulic brakes, the synchromesh transmission, power steering, and most recently the rotary engine.

Inventor-firms face great risk. For instance, in recent years G.M. has received about 5,000 calls and letters annually which urge the firm to adopt some new concept.

Few submissions, however, survive an initial screening: most are approaches already known to the company or are utterly fanciful. Approximately ten to fifteen percent of all suggestions survive the initial screening and are passed on to the various engineering departments of the corporation. Attrition here is also high and only about two inventors manage to sell their ideas to G.M. each year.¹²

Like the regular automotive vendors, inventor-firms tend to concentrate on the earlier phases of the inventive process. This is not surprising, since individual creative insight is the crucial ingredient at the beginning of the invention process. Moreover, the physical resources required for experimentation and testing at the beginning of the invention process are relatively small. Therefore, it is possible for the small firm to make important contributions.

The third class of technology producers are the automakers themselves. While the automakers rely heavily on inventive activity elsewhere, their own research organizations are impressive. In 1975, for instance, G.M., Ford and Chrysler ranked first, third and tenth in R&D spending among 730 top U.S. corporations.¹³

The sequential nature of the invention process is reflected in the organizational structure of the Big Three. At G.M., basic and applied research and exploratory development are centered at the G.M. Research Laboratories.

Alfred P. Sloan, writing in 1963, described the three main kinds of works carried on by the Research Laboratories:

First, it does trouble-shooting around the corporation and it may be called in to help wherever its specialized knowledge is needed, for example in the elimination of gear noise, in the testing of castings for material defects, or in the reduction of vibration. Second, it makes engineering improvements of a creative nature, growing out of problem solving. These problems range from improvements in transmission fluids, paints, bearings, fuels, and the like, to high-level applied research such as work on combustion, high-compression engines, refrigerants, diesel engines, gas turbines, free-piston engines, aluminum engines, metals and alloy steels, air pollution and the like. And third, it encourages some intensified basic research.¹⁴

Advanced engineering at G.M. is largely conducted by the "Engineering Staff"; this entity, like the Research Laboratories, is part of the corporation's "Operations Staff." Here takes place a "continual process of research and testing in four vital areas--power development, transmission development, structure and suspension development, and the design of new types of cars."¹⁵ The Engineering Staff also advises top management on the commercial possibilities of new designs and it acts as a consultant to the car-making divisions.

A third tier of research departments is located at G.M.'s car-making divisions. Production engineering is centered at this level. To avoid needless duplication, the divisional departments do not work in complete independence; in recent years, for example, Buick has been the "lead" division in carburetion work, while Oldsmobile did much of the final work on the catalytic converter.¹⁶

General Motors' R&D network is directed by a number of committees and policy groups. More informal, and much more frequent, intra-corporate contacts are also important in the coordination of the firm's R&D efforts.

The organization of R&D at Ford is similar. Basic and applied research is conducted by the Scientific Research Staff. Another "operations" staff, Product Planning and Research, does exploratory development, or, as Ford has stated, is responsible "for investigating long-run product improvements on a world-wide basis."¹⁷ Ford's work on exotic engines is centered here. The activity of the two operations staffs overlap in the area of applied research.

Advanced development at Ford takes place at the Car Research section of the Product Development Group. Design concepts that are approved for production engineering become the responsibility of another section of the Product Development Group, Car Engineering. This section coordinates and shares final development with the product engineering offices located in the Manufacturing Group. Except for the Automotive Assembly Division, all of Ford's manufacturing divisions--Transmission, Engine, Body, Chassis, and General Products--have product engineering offices that are responsible for the final engineering details of their own automotive components.

As at G.M., the coordination of Ford's R&D network is done by formal committees and informal personal communications.

Much the same is found at Chrysler. The earlier stages of R&D are conducted "above" the manufacturing divisions. At Chrysler the work is the responsibility of the Product Planning and Development Office. This is the location of Chrysler's Research Office, which is itself divided into a Basic Science and an Applied Research section. Chrysler's description of the responsibilities of the directors of these two sections is informative:

The Chief Research Scientist, Basic Sciences Research, is responsible for research in physics, chemistry, metallurgy, instrumentation, and human engineering. He conducts research in materials and processes and directs studies in general experimental, theoretical and solid-state physics, human engineering, vehicle and component dynamics, and electric systems. The development of catalytic materials and manufacturing processes for same has been a major responsibility.

Since 1969, the Chief Research Engineer, Applied Research, has been responsible for research on automotive power systems, including internal combustion engines, external combustion engines, electrical power, and on power system applications such as total energy. He conducts research on vehicle systems, including emission control devices, and research in aerodynamics, thermodynamics, and mechanical systems as applicable or related to research projects or Corporate projects.¹⁸

Obviously, some of the activity in the Basic Sciences section could be called applied research, while some of the work in the Applied Research section could be called exploratory development.

Advanced development at Chrysler takes place in another part of the Product Planning and Development Office, the Advanced Engineering Office. Advance work on new model cars and the development of new components is carried on here.

The final steps of product development are largely the responsibility of the Engineering Office, which, with Chrysler's manufacturing operations, is located in the firm's North American Automotive Group. The Engineering Office is divided into four functional areas of responsibility: Body Engineering, Engineering Operations, Materials Engineering, and Vehicle Engineering.

As at Ford and G.M., coordination of Chrysler's R&D network is by committees and informal contacts.

These sketches of the Big Three's R&D organizations belie their complexity and bulk. Most of the corporate entities mentioned are subdivided into many departments, sections, groups, etc. For instance, the Body Engineering Office at Chrysler is divided into over 25 sections; the Product Engineering Office of Ford's Engine Division has over fifty sections, each of which is assigned to some particular task or responsibility.

Recent annual expenditures by the domestic automakers on research and development are presented in Table 1. Although Ford seems to be closing the gap, G.M. is the industry leader in R&D expenditures. The expenditures of the smallest domestic automaker, American Motors, are miniscule by comparison. Earlier evidence suggests that G.M. has led the industry in R&D expenditures since the 1920's.

The monetary differences in the R&D budgets of the automakers show up qualitatively as differences in (1) the

TABLE 1
Corporate R&D Expenditures
1967-1978

Year	G.M.	Ford	Chrysler	A.M.C.
1967	664	325	75	--
1968	736	359	84	--
1969	825	423	95	--
1970	808	453	81	--
1971	900	513	90	--
1972	945	621	124	--
1973	1077	826	149	--
1974	1090	849	150	38
1975	1113.9	747	199	36
1976	1257.3	924	280	39
1977	1451.4	1170	286	43.3
1978	1633.1	1464	344	48.4

Sources: Chrysler Corporation, "Request for Suspension of the 1977 HC and CO Emission Standards," January 1975; Ford Motor Company, "Application for Suspension of 1977 Motor Vehicle Exhaust Emission Standards," January 1975; General Motors Corporation, "General Motors Request for Suspension of 1977 Federal Emission Standards," January 1975; Stockholders Reports, various issues.

number of projects undertaken and (2) the intensity of effort in given projects.

It appears that General Motors has the most broadly based R&D program while Ford, Chrysler, and AMC respectively have increasingly less diversified programs. An illustration is provided by the automakers' R&D projects for the control of automotive emissions. Table 2 presents a qualitative evaluation by the Environmental Protection Agency of these projects between 1970 and 1975. The efforts were broken down into 21 distinct programs. Looking at the programs for which comparable ratings are provided (all except alternative engines), G.M. led all rivals in seven program categories and lagged behind a rival in but four categories. Ford led in only two cases and it was beaten by a rival in nine programs. Chrysler's performance was on a par with Ford's: Chrysler was the industry leader in three categories while it lagged behind a rival in eleven. American Motors' efforts were far behind the Big Three; AMC led the industry in no categories; in nine program categories, AMC apparently could not afford any effort at all.

c. Patents and Property Rights

Technology has some of the characteristics of a collective good. Once new techtils are produced and revealed, it is difficult to prevent their use by outsiders. If no property-right device existed to guarantee exclusion, private technology-production would be severely discouraged.

TABLE 2
EPA Evaluation of Automotive R&D Directed Toward Emission Control
1970-1975

Program	AMC	Chrysler	Ford	GM
1. Cooperative Catalyst Development	None	Little	None	None
2. Combustion Studies	Little	Moderate	Extensive	Extensive
3. Noble Metal Catalyst	None	Little	Extensive	Extensive
4. Base Metal Catalyst	None	Moderate	Little	Moderate
5. 3-way Catalyst	None	None	Moderate	Extensive
6. Fuel and Fuel/Air Mixture	Moderate	Moderate	Moderate	Moderate
7. Improved Fuel Metering	None	Moderate	Moderate	Extensive
8. Advanced EGR Development	None	Moderate	Little	Extensive
9. Improved HC Control	None	Moderate	Little	Extensive
10. Ignition System Improvements	Moderate	Moderate	Moderate	Extensive
11. Combustion Chamber and Compression Ratio Studies	Moderate	Moderate	Moderate	Moderate
12. Improved Intake Manifold	Little	Moderate	Moderate	Extensive
13. Rich Thermal Reactor	Little	Moderate	Extensive	Moderate
14. Lean Thermal Reactor	None	Extensive	Moderate	Little
15. Air Injection Studies	None	Moderate	Moderate	Moderate
16. Oxidation Catalyst Improvement	Little	Moderate	Extensive	Extensive
17. Alternative Engines	Little	Adequate	Inadequate	Adequate
18. Reactor-Catalyst Reactor System	Little	Little	Little	Moderate
19. Better Dual Catalyst	Little	Moderate	Little	Little
20. Chassis/Body Optimization	Little	Little	Moderate	Extensive
21. Vehicle Systems Synthesis Studies	Little	Little	Little	Little

Source: U.S. Congress, Senate, Committee on Public Works, Implementation of the Clean Air Act.
Hearings before the Subcommittee on Environmental Pollution, 94th Cong., 1st sess.,
pp. 728-9.

Private technology-production would perhaps not disappear altogether since, in the real world, there is apt to be a lag between innovation by one party and imitation by others.

The public policy answer to this problem is, of course, a patent system. The pros and cons of the American patent system need not be reviewed. Suffice it to say, patents are imperfect property-right devices because technology-producers will always suffer from some uncompensated-for "leakage" of their output to other parties. The boundaries of patent rights are always ambiguous. And if one technology-producer receives a patent on a possibly valuable concept, this is free information that guides the work of others. In short, despite the patent system, at least some new technology will always emerge as a collective good. Nevertheless, it can be assumed that the bulk of new automotive technology can be privately held under the aegis of the patent system.

The automakers have not been overly aggressive in the exploitation of patents; instead, a spirit of cooperation has been the rule. Although formal agreements on patent pooling have been abandoned, the automakers continue to make patents available to each other on fairly liberal terms; the swapping of patents is not uncommon.

The nature of automotive technology no doubt has encouraged this behavior. Automotive technology has progressed in the form of marginal improvements in car components. The prospect that an innovation could

tremendously improve the quality of a car has been remote; since the return to an automaker is apt to be small, it is not surprising that the firms have displayed a "live and let live" attitude.

This is not to say that the automakers do not seek patent rights when they can. Patents give protection from litigation, especially litigation involving non-automakers. A less important reason for seeking patents is the maintenance of corporate morale: firms may encourage their research people to apply for patents (though under most employee contracts patent rights are assigned automatically to the firm) so the individual's work in the lab may be duly recognized and applauded.

3. The Supply of New Automotive Technology

This section analyzes the supply of new automotive technology.

The supply of any output depends on the relevant production function and resource prices. In the case of new technology, the latter does not create any special analytical problems; if prices of research labor services or laboratory test equipment increase, this will tend, ceteris paribus, to decrease the supply of new technology; a decrease in resource prices will tend to increase supply.

However, the production function for new technology presents difficulties. It is not well-defined (that is, it is not a stable relationship) and it is hard to find practical units to measure inputs and outputs. Moreover,

as one moves from early to later phases of the invention-process, it seems that production function changes form. Indeed, one might take the approach of positing separate production functions for each phase of the invention-process. If so, a few observations can be offered. First, the resource cost required by a phase of the invention process is apt to increase as one moves from earlier to later phases. The auto industry's experience with engine development is illustrative. The research and exploratory development of a new internal combustion engine usually costs between ten and twenty million dollars. Generally, ten to twenty primitive prototypes are built during this phase. The next phase, advanced development, is more costly "because of the larger staff, increased vehicle hardware procurement and fabrication, and the extensive test facilities and support required."¹⁹ Twenty to fifty prototypes are apt to be built in advanced development, and the total cost of this phase may run from 20 to 150 million dollars. The costs of finishing the manufacturing program are apt to be higher still. Counting final pre-innovative development, plus procurement of manufacturing facilities and tooling (which are really costs of innovation, not invention), an additional 300 to 500 million dollars may be spent.

Why does this pattern of increasing resource cost exist? Remember, invention is a process of experimentation and observation. It involves the positing of hypotheses

(or, less formally, the making of hunches), and the design of experiments to test hypotheses. During the earlier phases of the invention process, the hypotheses are relatively few and simple; researchers are chiefly concerned with the mere existence of the looked-for effect. Only a relatively small number of experiments of restricted scope are apt to be needed. As a result, the resource cost is likely to be small.

On the other hand, the later stages of the invention process require a more full knowledge of the phenomenon under investigation. More hypotheses are needed and more experiments must be designed and run. Moreover, the hypotheses and testing must increasingly reflect the constraints imposed by the everyday world outside the lab (costs, durability, safety, etc.). All of this tends to make technology-production more expensive.

Another characteristic of the invention process is that the production functions of early phases are less well-defined than those of later ones. The resource-sacrifice required to meet the objectives of, say, production engineering, tends to be much easier to predict than the sacrifice required by applied research. The varying role of creative insight is probably responsible for this pattern. During the earlier phases of the invention process creative insight is crucial: the production of new and exotic knowledge requires imaginative hypotheses and imaginative experimental design. In contrast, while

experimentation during the later phases is apt to be more tedious and involved, creative insight is apt to play a smaller role since earlier breakthroughs have shown the general direction in which the work should proceed. Therefore, since creative insight cannot be varied at will, its unpredictable volatility as an input manifests itself more strongly in the earlier phases of the invention-process.

The differences in the stages of the invention-process have important implications for entry. Capital costs tend to be lower at the earlier phases. Entry at those phases, therefore, is easier, ceteris paribus, while effort at the final steps before innovation requires a financial stake that makes entry more difficult. On the other hand, entry at earlier phases tends to be discouraged by the great instability of the production function. Profitable operation is highly uncertain and, as a result, the securing of funds from capital markets is difficult. While it is not clear how these factors balance out, it is likely that successful entry is easiest at the middle phases of the invention-process: it is noteworthy that the efforts of small inventor firms appear to be concentrated in this area.

Now consider the invention-process as a whole. Imagine a grand production function that integrates the production functions of the various phases.

It appears that the supply curve for individual technology producers is upward-sloping. The cost of producing new automotive technology is usually expressed in terms of

what it takes to complete a particular research project; the time required to complete a project depends on the rate of resource commitment. Shortening the duration of a research project, in comparison to normal practice, increases the total cost of the project.²⁰ (See Figure 1.) It is unclear, however, whether the time-cost curve turns up for longer-than-normal projects. At best, it can be concluded that the curve must flatten out at some point, for if it did not, the implication is that a given number of techtils could be produced at zero cost.

If the total cost of producing a given number of techtils increases as a project's duration is compressed, cost per techtil, the average cost of technology-production, must eventually increase as the rate of techtil production is stepped up. And if average cost increases, the marginal cost of production must increase even faster. Figure 2 illustrates these relationships.

Since the technology-production function is probabilistic, the average and marginal cost of techtil production must be expressed as expected values.

At this point, the usual association of marginal cost and supply can be made. Moreover, an analogy can be made between the individual research project and the economist's concept of the plant. The technology-producer which is conducting a number of research projects is a multi-plant firm. This raises the question of the existence of economies of multiple research projects similar to multi-plant

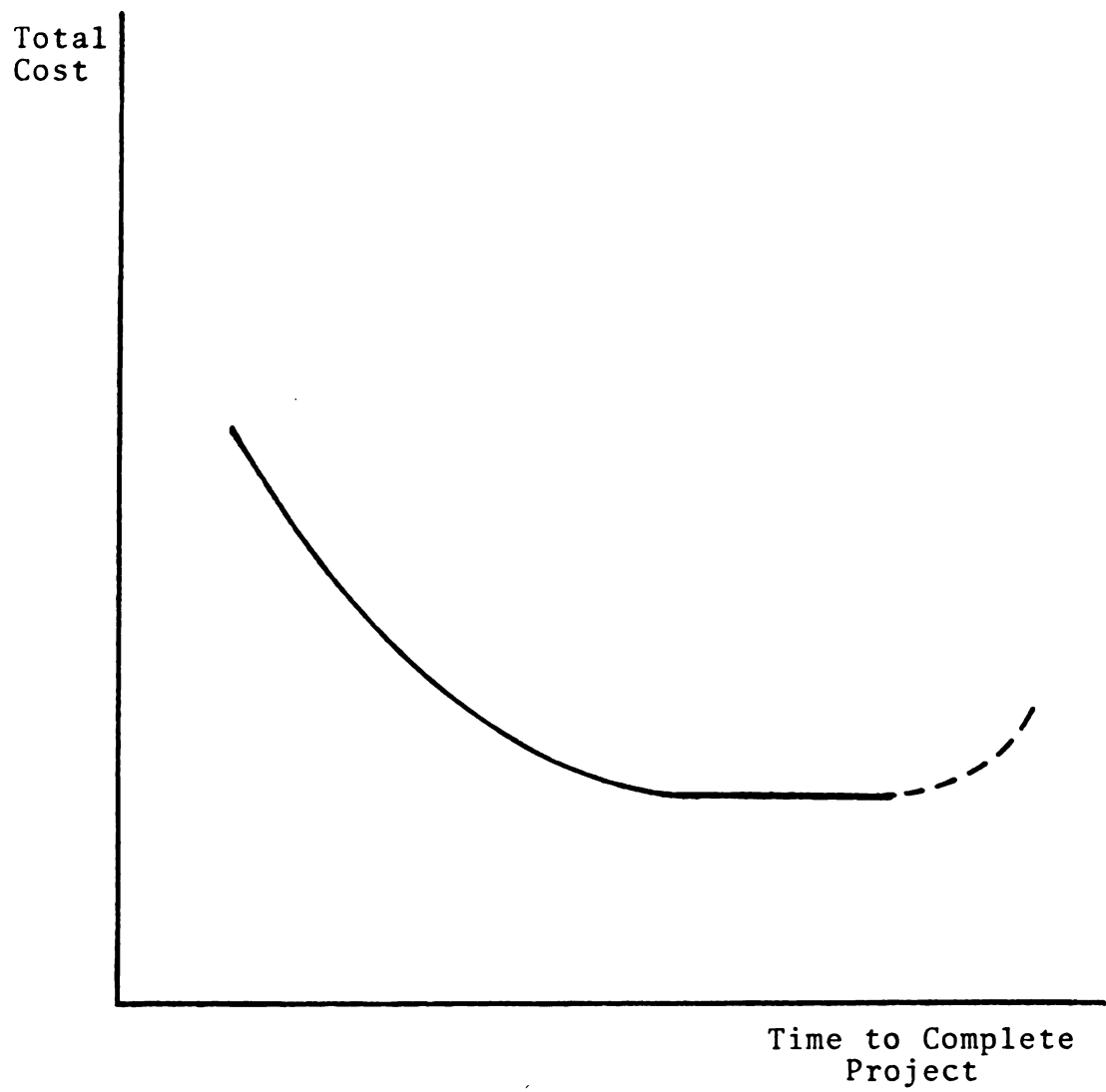


FIGURE 1

Relation Between Cost and Time
for Completion of an R&D Project

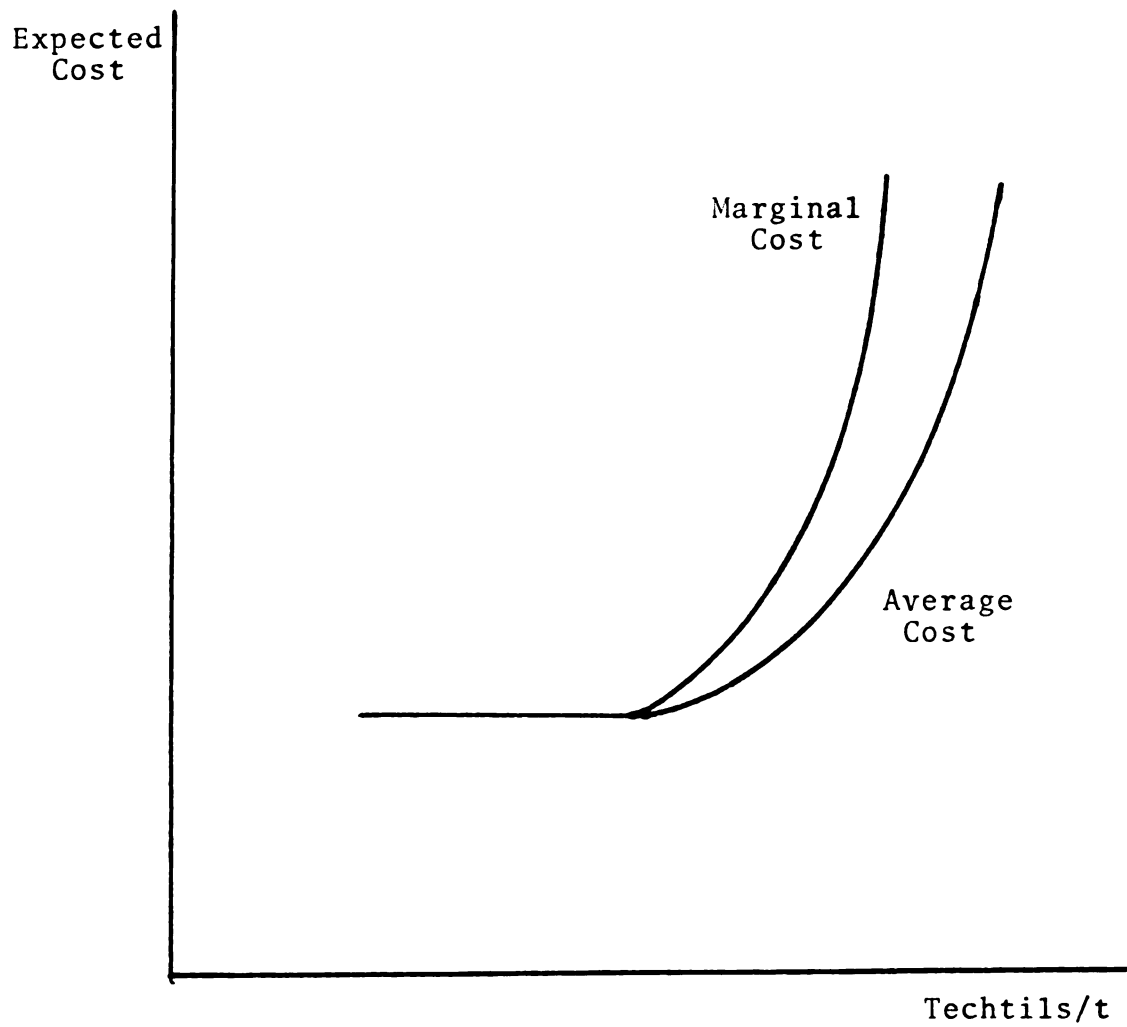


FIGURE 2

Average and Marginal Cost of
Technology Production

economies; unfortunately, no evidence can be offered on this matter.

The total supply of new automotive technology in a given direction is merely the sum of the individual "plant" supplies of the technology-producing firms. Entry by new technology-producers will increase total supply.

Finally, there is the matter of "technological opportunity." The possibilities for increasing knowledge in a given direction vary over time. New products, it is often maintained, are easier (i.e., less costly) to improve than mature ones. Perhaps there are diminishing returns to the basic creative insights which made the product possible. An exhaustion of technological opportunities would shift the supply of new technology to the left. One suspects this tendency has been at work in the automotive field; that is, it was easier to improve the auto in 1910 than it was in 1970. It is conceivable, however, that new creative insights could enlarge technological opportunities and, as a result, shift the new technology supply curve to the right. A possible example is the fundamental advances in electronics, which have made possible new and better ways of regulating the operations of automotive engines. At any rate, the variance of technological opportunities over time is another manifestation of the erratic nature of the technology-production function.

4. Demand for New Technology in General

This section presents a model of the demand for new technology. In the next section, this model is discussed in the context of automotive technology.

a. The Firm's Decision Situation

The demand for new technology is based on its potential to increase the profits of product-producing (as opposed to technology-producing) firms. In product innovation, the firm "enters" a new product space, attracted there by profits which appear greater than those being earned in the old product space. The cost of entering new product space is cost of acquiring the necessary new technology; the product-producing firm may incur this cost in its own technology-producing departments or may pay other technology-producers for the new knowledge.

Consider one direction of the new technology vector. In that direction, assume that a firm perceives a number of potential innovations. These innovations embody different amounts of new techtils: radical innovations contain, by definition, a large number; refinement-type innovations, a lesser amount. Assume the firm is indifferent to whether a given number of techtils is embodied in a few radical innovations or in many refinement-type innovations.

Let $\pi(T)$ represent the present value of the expected profit flow, above that which the firm earns in old product space, due to the innovation of T techtils. Let

$C(T)$ be the expected cost of acquiring T techtils. Assume that there is no lag between acquisition of the new technology and its introduction to the market; also assume that the set-up costs of innovation are zero. Furthermore, assume for the moment that the firm will enjoy a monopoly in the new product space that it enters. Let the expected present value of T techtils be given by

$$(1) \text{ PV}(T) = \pi(T) - C(T).$$

The portion of this function that is relevant for decision-making is where $\text{PV}(T)$ is positive; call this portion the innovation-possibilities curve (IPC).

The shape of the IPC depends on the nature of the cost and profit functions. It is clear that $C'(T) > 0$; in addition to the fact that more techtils cost more, ceteris paribus, it is possible that the firm's own purchase may drive up the price per techtil. As far as $\pi(T)$ is concerned, it seems safe to assume that after some point there are constant or decreasing returns to innovation. That is, after some point $\pi''(T) \leq 0$ with $\pi'(T) \leq K$. Assume, therefore, that the IPC is concave to the horizontal axis. Figure 3 illustrates.

The innovation-possibilities curve is a probabilistic function: the present value of any rate of innovation is uncertain. The degree of uncertainty varies monotonically with the rate of innovation. Consider the difference between a refinement-type innovation and a radical one. A refinement-type innovation is a good that is only slightly

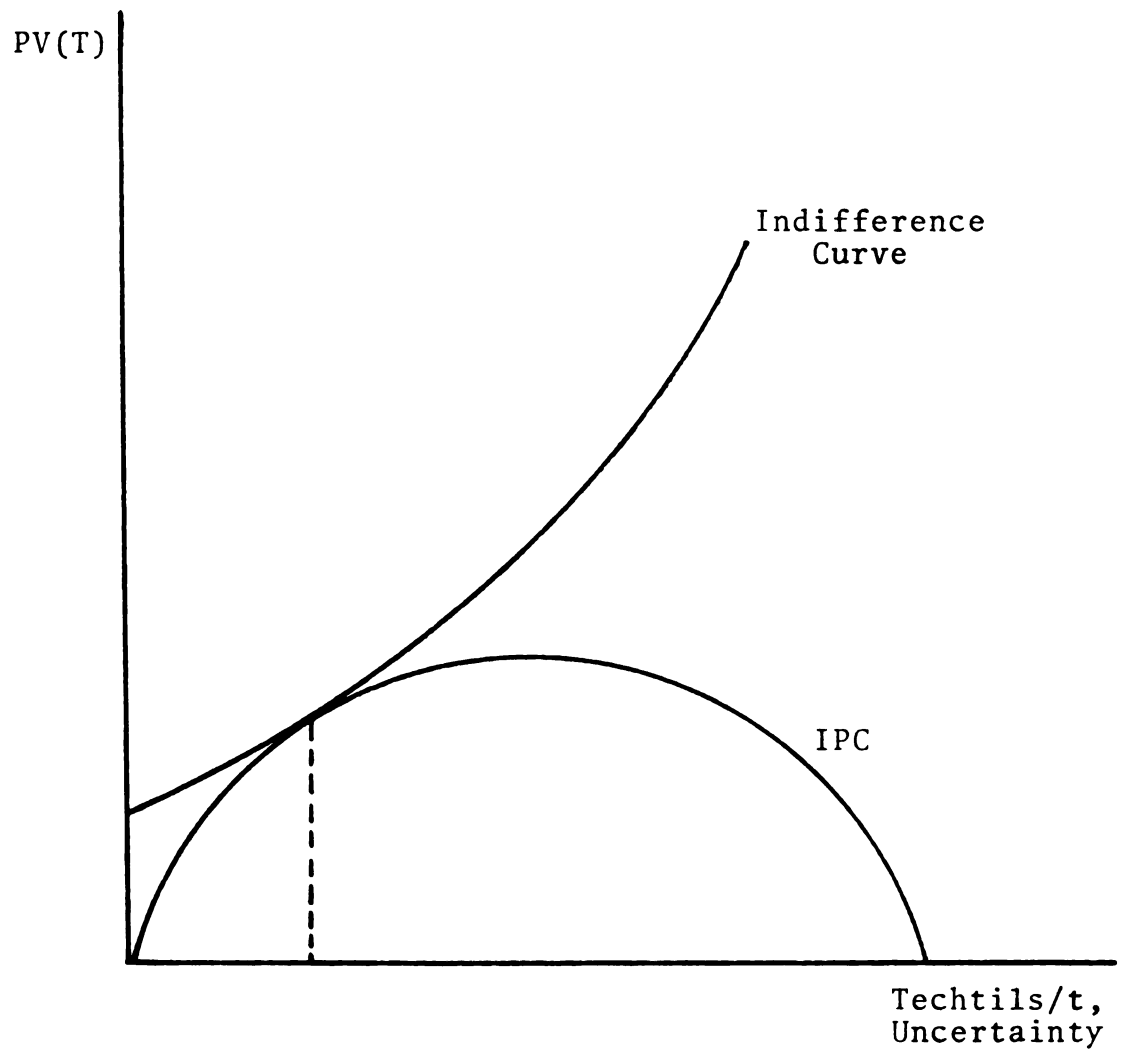


FIGURE 3

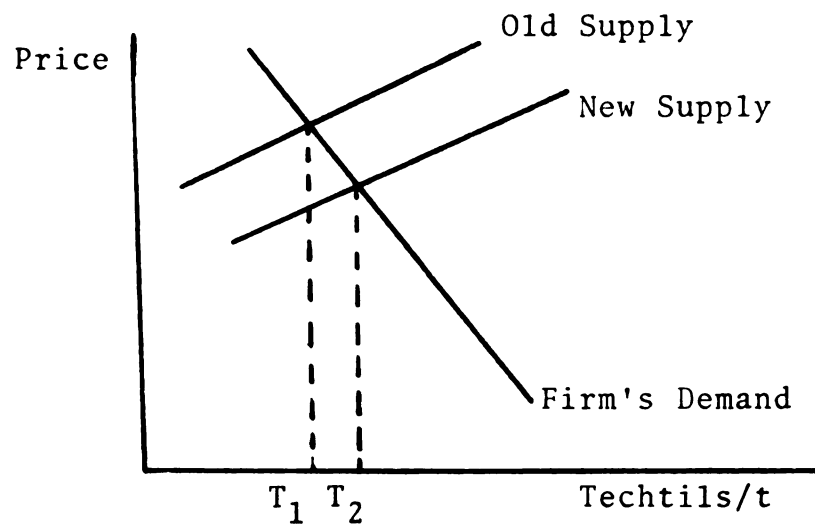
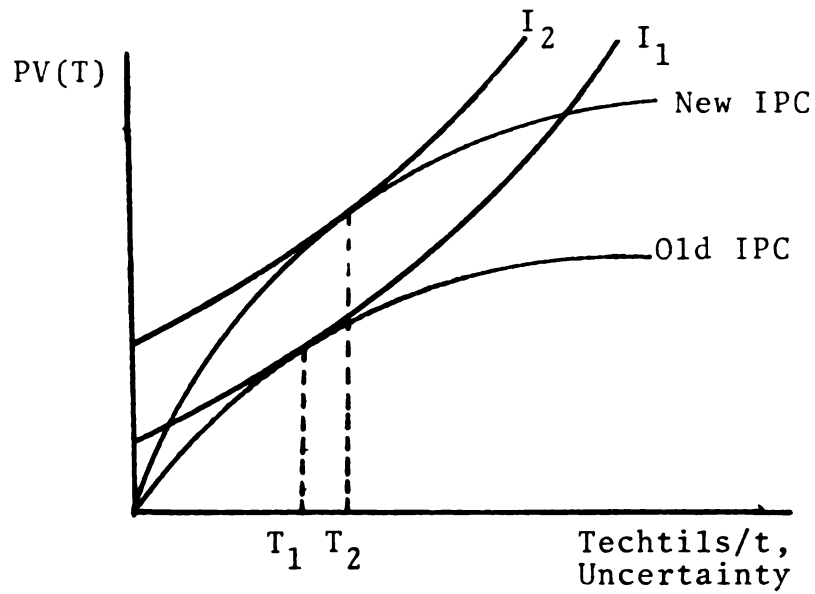
Utility Maximization for a Monopolistic
Innovator

different from existing goods and, as a result, its demand is apt to be similar to existing goods; furthermore, the uncertainty of refinement-type innovations is fairly low. In contrast, the demand for a radical innovation cannot be as easily inferred from demands for existing goods. Moreover, uncertainty about the cost of technology acquisition is apt to increase with the rate of innovation.

Let the uncertainty of innovation be measured by the variance of the present value of $PV(T)$. Assuming that uncertainty increases with the rate of innovation, the horizontal axis of Figure 3 can serve double duty by indicating both the rate of innovation and the uncertainty associated with that rate.

Now assume that the firm's decisions on innovation are based on a utility function whose arguments are expected present value and uncertainty. Risk aversion is the most likely characterization of the firm's attitude towards uncertainty; assume, therefore, that the firm's indifference curves, when plotted in present value-uncertainty space, are positively sloped, and reflect the usual property of diminishing marginal utility.

For a given set of preferences and innovation-possibilities, there exists a utility-maximizing level of innovation for the firm. Point A in Figure 4-a represents one such equilibrium. This point implies a certain level of innovative effort by the firm. This level, in turn, implies a certain demand for new technology by the



FIGURES 4-A AND 4-B

Derivation of a Firm's Technology Demand Curve

firm--or more precisely--a point on the firm's new technology demand curve. Moreover, assuming for the moment that the firm is the only buyer of new technology (but ignoring any possible monopsony effects), this equilibrium level of quantity demanded equals the quantity supplied. This being so, the entire technology demand curve can be determined by imagining alternative technology supply curves. Thus a second point on the firm's new technology demand curve could be identified if the supply of new technology increased. The IPC would be pushed up, although it would remain anchored at the origin. As Figures 4-a and 4-b show, a risk-averse firm would likely increase its innovative effort from T_1 to T_2 .

b. The Role of Capital Markets

A firm's innovation-possibilities are more attractive if interest rates are low. Firms that finance the purchase of new technology from returned earnings are encouraged to innovate since the opportunity cost of technology investment is low. Similarly, firms that borrow to purchase new technology are encouraged by small interest charges. High interest rates, on the other hand, make the firm's innovation-possibilities less attractive. As a result, an increase in interest rates would reduce the firm's demand for new technology, ceteris paribus.

c. Consumer Factors

These factors include the tastes and incomes of consumers, the prices of substitutes and complements of innovations, and the size of the population. These factors determine the profitability of new products. For example, an increase in consumer income is likely to make innovation more profitable; such an increase would shift the IPC upwards, and would tend to increase the firm's demand for new technology.

d. Rivalry in New Product Space

In the context of innovation, rivalry has two forms. The first is imitative. Firm A, for instance, brings out an innovation which embodies T_1 units of new technology. Imitation occurs when Firms B, C, etc., merely copy A's new product without compensating A; imitation is prevented, however, if Firm A has secure patent rights.

But even with patents, a second form of rivalry is possible. Here Firm A brings out an innovation while rivals introduce innovations outside Firm A's patent coverage, which nevertheless are reasonably close substitutes for Firm A's innovation. Call this form of rivalry "counter-innovation."

If the firm has imitating or counter-innovating rivals in new product space, it cannot expect to capture as much profit as a monopolist; for any T , $\pi(T)$ is less than that under monopoly. This effect, ceteris paribus, reduces the

incentive to innovate and, as a result, tends to reduce the firm's demand for new technology.

However, the presence of rivals increases uncertainty for the firm. Under the monopoly case, the firm suffers no uncertainty if it chooses not to innovate: the present value of no innovation equals zero. This is not true if innovating rivals are present. Here, the non-innovating firm may suffer losses if rivals innovate successfully, since it may find its products becoming obsolete. In other words, the value of $\pi(T)$ at $T=0$ is apt to be negative and not known with certainty. Therefore, under rivalry, the firm's IPC shifts down and to the right. The extreme left point of the curve, which still implies zero innovation by the firm, is no longer anchored at the origin but lies somewhere to the southeast. Figure 5 illustrates.

It is indeterminate whether the individual firm will innovate more under monopoly or under competition. To some extent, the firm will be discouraged from innovation since imitation and counter-innovation reduce the expected present value. But, on the other hand, the firm will be encouraged to innovate by the fear that rivals will make its existing products obsolete. Theory does not tell us whether the carrot is stronger than the stick.

The effect of competition on the individual firm's demand curve for new technology is similarly ambiguous. To the extent that the present value of innovative effort is reduced by competition, the firm's demand for new

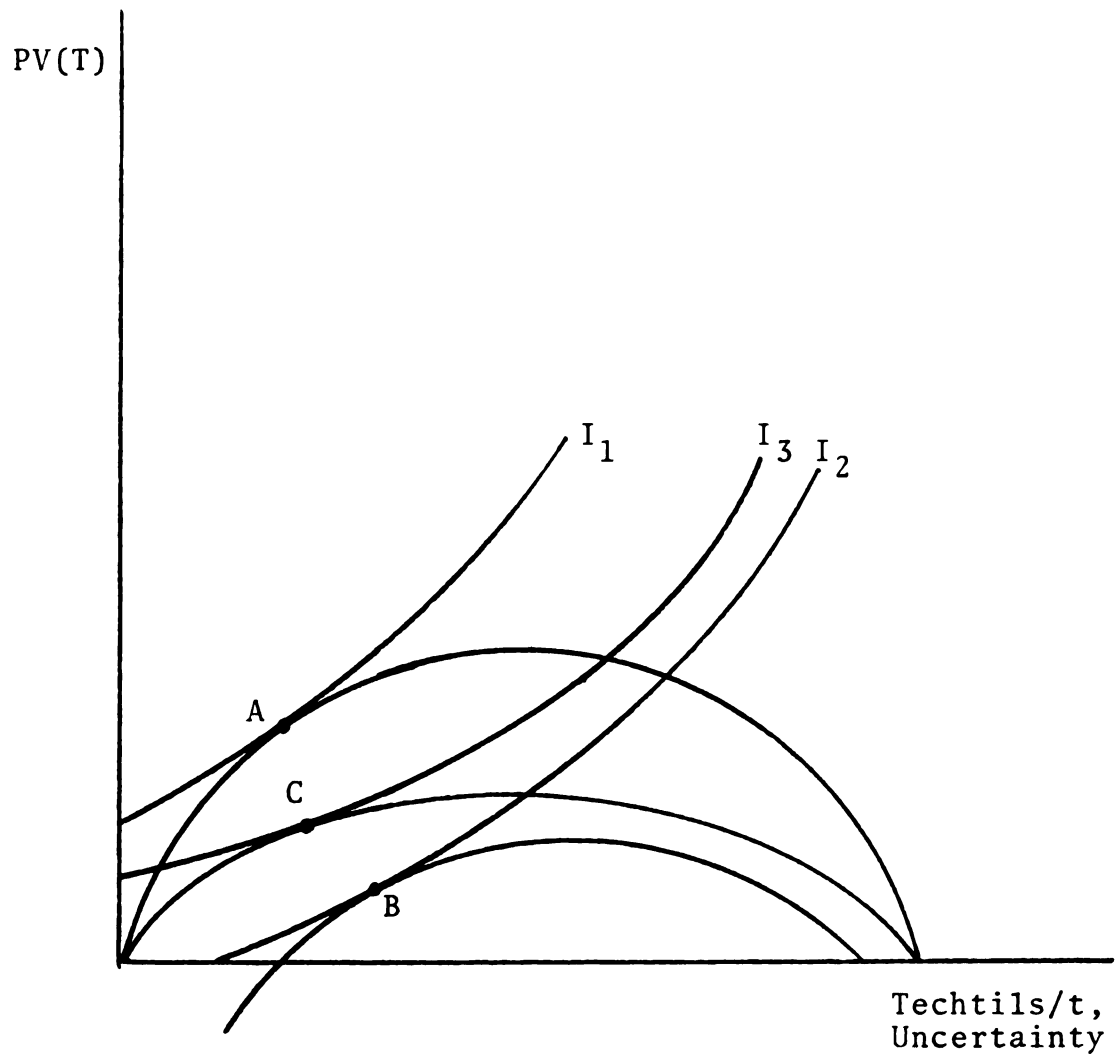


FIGURE 5

Firm Equilibria under Monopoly,
Collusion, and Competition

technology will be lessened; to the extent that the firm is fearful that rivals may score an innovative coup de grace, the firm's demand will tend to be greater.

Note that with competition, the firm operates at a lower level of utility, denoted by indifference curve I_2 : hence, a motivation for collusion. If firms cooperate, "ruinous" competitive innovation could be reduced or eliminated entirely; collusion would drive surprise out of the industry and, as a result, lessen uncertainty. A rate of innovation could be set which had the effect of increasing the present value of innovation and is consistent with the firms' preferences on uncertainty.

The collusion case is also illustrated in Figure 5. Since uncertainty over rivals' strategies has been reduced, the firm's IPC moves to the left and upward. If uncertainty about rivals is eliminated entirely, the curve, as in the case of monopoly, begins at the origin.

In Figure Five, the firm is in equilibrium at point C. In terms of utility, this point is superior to point B where competition is unconstrained, but not to point A, the monopoly case, since the firm must share the rewards of innovative efforts with its fellows. The effect of such collusion is to reduce the firm's demand for new technology.

The factors that encourage collusion of this sort are the same which encourage the traditional kind of collusion on price. These factors include fewness in the number of

firms, a mechanism for coordinating change such as dominant firm leadership, free flow of information between firms, and similarity in preferences and goals.

e. Pre-Innovation Market Position

There are two effects of sales and profitability on the firm's willingness and ability to innovate. The first is the possibility that a large market share in old product space may help the firm capture the profits accruing to an innovation; in other words, the value of $\pi(T)$ is enhanced due to a favorable market position in the sale of old products. The well-established firm may enjoy the advantages of efficient channels of distribution or a well-known name. As a result, the firm may be able to achieve a high rate of sales of its innovations in a short time, or be better able to keep ahead of imitators and counter-innovators. Consequently, good pre-innovation market position may tend to increase the firm's demand for new technology.

The second effect of sales and profitability has to do with the cost of new technology. Entry into new product space by innovation is like entry into markets of already existing goods; in the latter, a certain minimum amount of capital is required to start up operation. However, new firms which must appeal to capital markets may find entry impossible: lenders tend to view new firms as risky and are apt to charge relatively high interest rates; indeed, if the capital requirements are very large,

new firms may not be able to secure the necessary loans at any interest rate. Profitable and well-established firms, on the other hand, are apt to have an easier time in dealing with the capital requirements for entry. Entry may be financed through retained earnings: in effect, the firm borrows from its stockholders, implicitly promising a greater return in the future. And if the firm does appeal to the capital markets, it is apt to secure loans on terms more favorable than those offered to the new firm.

Similarly, entry into new product space requires the financing of a certain amount of new technology; the more radical the innovation, the greater the likely requirement. Small firms may have trouble overcoming the technology-requirement barrier to new product space; or they may be limited to relatively minor innovations. To be sure, the unpredictability of the technology-production function may offer fairly radical innovations whose cost is within the reach of firms with limited financial resources; in other words, the height of the technology-requirements barrier, due to the erratic nature of technology production, is variable. Nevertheless, there may be a tendency that high levels of sales and profitability encourage innovation. As a result, the new technology demand curve of the prosperous, well-established firm may be greater than that of a lesser firm, ceteris paribus.

f. Market Demand for New Technology

The market demand for new technology, in a given direction, is simply the sum of individual firm demands.

5. Demand for New Automotive Technology

a. Preferences of the Firm

It may be safely assumed the managements of the automobile companies are risk-averse. However, the degree of risk-aversion may vary from one management team to another. The presidency of Edward Cole at G.M. during the late 1960's and 1970's, for example, has been cited as being responsible for that firm's relatively progressive conduct with respect to the catalytic converter and the rotary engine.²¹ In short, an auto firm's demand for new technology is affected by who is running the company.

b. The Role of Capital Markets

The discussion of the role of capital markets, which was presented in section four, needs no elaboration.

c. Consumer Factors

Most car buyers cannot readily judge the technical merits of alternative design configurations. As a result, consumers tend to focus on styling and those engineering features which they easily perceive as adding to performance, convenience, or comfort. In other aspects of design, the incentive for the manufacturer is to select technology that minimizes the cost of production, subject to quality constraints.

Automotive innovation is sensitive to consumer income. To a great extent, real income determines the premium that consumers are willing to pay for an innovation. Premiums are necessary not only to reward the investment in new technology, but to cover the increase in production cost which usually accompanies quality-improving innovations.

Clearly, quality and novelty are more important to wealthy buyers. It is not surprising, therefore, that most innovations have been introduced on the higher-priced car lines first. The record of firms such as Packard, Duesenberg, Stutz and Mercedes-Benz support this impression. A large number of G.M.'s innovations have been brought out on that firm's highest-price line, Cadillac.

Moreover, a general rise in consumer income encourages innovation. The upgrading of cars during the 1920's and the decade or so following World War II, was no doubt encouraged by the growing prosperity of most Americans. A decline, or perhaps merely a stabilization, of incomes makes innovation less attractive to firms. The bad economic conditions of the early 1930's, for instance, led G.M. to postpone the introduction of the automatic transmission to the end of that decade.²²

The last consumer factors to be considered are the prices of other goods. General equilibrium analysis teaches that the prices of all substitutes and complements affect the profitability of innovation.

However, in anticipation of the following chapters on alternative automotive engines, it is worthwhile to restrict attention to just three prices. The most important substitutes for an innovation are the goods or design configurations which it seeks to displace; in the case of alternative engines, this is the price associated with the now dominant design configuration, the Otto cycle, internal combustion engine. The most important complements of automotive engines are fuel and maintenance services.

It is noteworthy that historically low fuel prices in the United States have influenced American engine design. As early as World War I, differences in American and European practice were apparent. After noting the higher price of gasoline in Europe, one prominent automotive engineer in 1921 remarked:

American cars have sold and are still selling in Europe in large numbers, because they have a great reputation for reliability, and they can always be bought from stock, but they do not show to such a great advantage in Europe as in America. The reason for this is that their engines are, from the European point of view, too big for the performance obtained from the car. In other words, they consume too much gas.²³

Other articles of similar content may be found in later editions of automotive trade journals. It was not surprising, therefore, that the most fuel-efficient car sold in the U.S. during the 1970's was designed in West Germany instead of Detroit.²⁴

d. The Presence of Rivals in New Product Space

Although their position has been threatened in recent years by foreign auto-makers, the Big Three have dominated the U.S. automobile market throughout the post-war era. Collusion is not unlikely in such a tight oligopoly; indeed, tacit collusion on pricing appears well-established, with G.M. in the role of price leader.

It is now argued that product competition has also been restrained by tacit collusion. The lessening of uncertainty and the easing of the downward pressures on profits due to competition are the goals of such collusion. Its effect is to reduce the industry-wide demand for new technology.

A review of the industry's history is enlightening. The industry's history can be divided into three parts. During the first, which may be called the formative era, the industry was made up of many firms; barriers to entry were low and no firm dominated the industry. This period came to an end by the First World War. The formative era was followed by the early oligopoly; during this period the industry came to be dominated by three firms; in addition, however, there remained a fringe of smaller firms; entry by this time had become difficult, if not impossible. The early oligopoly was followed by the mature oligopoly. The boundary between these periods is not distinct; the years between the mid-thirties and early fifties are ones of transition. The structural evolution of the industry

is not especially noteworthy in itself: its significance is the resulting impact on industry conduct.

The striking features of the formative era were the great uncertainty of doing business and the individual firm's powerlessness in coping with it. Product innovation was fast-paced. Frequent and extensive redesign meant relatively large expenditures for new dies, jigs, templets, and machinery. Success in picking the right design seemed to depend as much on luck as insight, and the firm could not rely for long on consumer loyalty.²⁵

No doubt many producers would have preferred an easier life. But collective restraint was made impossible by the ease of entry and the large number of firms. To make matters worse, some firms seemed nearly indifferent to risk, as Benjamin Briscoe, an important automotive pioneer, once recalled:

In the spring of 1908, the conditions that confronted the automobile industry were thought by some of us to be somewhat ominous, especially for such concerns as had large fixed investments in plants, machinery, tools, etc. Not a few of the concerns of the day were run by what might have been called "manufacturing gamblers."

In many cases, the management had adopted methods that were described as "plunging." In fact we all plunged, and conditions came about which were thought by some of us to predicate disaster. The influence of several companies was always exciting and sometimes disturbing. The business of even the sanest among the manufacturers was influenced by them, for they had to submit into business risks which they would not have entered had they not been fearful that some other concern would gain a few points on them.²⁶

Uncertainty, the powerlessness of firms, and the intense competition between them, combined to make market shares highly unstable; of the top ten sales leaders in 1903, for example, only one (Ford) remained a leader in 1924.²⁷ That firm conduct contributed to the instability of market positions is a fact that cannot go unstressed. Firms made product decisions independently of each other and, as a result, there was a great diversity in product policies. Such diversity, with the usual fickleness of consumer preferences, made instability inevitable.

Now consider competition during the early oligopoly. By World War I the industry had become highly concentrated; the interdependence of market shares became keenly felt. Moreover, smaller firms were falling by the wayside, and high barriers to entry prevented a replenishment of the ranks.

However, the evolution of conduct lagged behind that of structure.²⁸ There appeared to be little or no collective behavior to constrain competition. Moreover, each major firm asserted a distinct brand of product policy.

Ford was dedicated to the production of low-price cars. Styling and change for change's sake had little place in the firm's product policy. Henry Ford himself:

We cannot conceive how to serve the customer unless we make him something that, as far as we can provide, will last forever. It does not please us to have the buyer's car wear out or become obsolete. We want the man who buys one of our products never to have to buy another. We never make an improvement that renders any previous model obsolete.²⁹

At Chrysler, excellence in engineering was emphasized. During the twenties the firm was prominent in the development of more powerful engines and the use of design configurations formerly seen only on more expensive makes. Chrysler was responsible for a number of innovations such as the use of rubber in the mounting of components and for insulation, rust-proofing, and advances in transmission design. The aerodynamic body and the scientifically designed suspension system of the 1954 Chrysler Airflow were the classic examples of the firm's zeal for engineering.³⁰ That car, because of its radical nature, was singled out by G.M.'s Sloan as not the way to build mass-produced automobiles. Chrysler's R&D laboratories were praised in the press on a number of occasions.³¹ To be sure, Chrysler did not ignore styling as an element in the selling of automobiles, but it was clearly subordinated to engineering.

General Motors' product policy, on the other hand, stressed "the very great importance of styling in selling."³² This was by no means a novel or revolutionary idea when it became part of G.M.'s product policy during the early twenties. G.M.'s contribution was a refinement and unprecedented mass-market application of this approach. Styling changes were relied upon to "create a certain amount of dissatisfaction"³³ among the owners of older cars. G.M. certainly did not ignore engineering improvements in car

design, but in this area the corporation's policy was conservative. Alfred P. Sloan wrote:

The policy we said was valid if our cars were at least equal in design to the best of our competitors in a grade, so that it was not necessary to lead in design or run the risk of untried experiments.³⁴

When such differences in product policies exist, the stage is set for a reallocation of market shares. In 1907 Ford was the maverick by bringing out a low-price car. That decision enabled Ford to capture over 50 percent of the market by 1920. But by the mid-twenties, the demand for new, cheap cars had been largely exploited; by then a large stock of used cars offered a good alternative to the purchase of a new car, even a Model T. The selling of new cars increasingly became something more than providing "basic transportation." The product policies of General Motors and Chrysler were more in line with the market's demand for something new and, consequently, both firms surpassed Ford in sales.

Conduct in the mature oligopoly has been of a different sort. Here the product policies of the major firms are remarkable for their similarities. This had become apparent by the late fifties. In 1958 George Romney, president of American Motors, noted that there was a "concentration of the three largest companies on the same product philosophy," viz., that of General Motors; Romney added:

Ford's adoption of General Motors' product policy was gradual but became complete in the period of Ford internal reorganization following World War II.

Chrysler, under its present management recently adopted it, and gave it full expression with the forward look and fins Now that wasn't conspiracy. It wasn't the result of anything other than the other two doing what the champ had done, and the result is that there has been a concentration in that area.³⁵

In contrast to the formative era, decision-making on product design is highly interdependent. Imitation, with a conservative degree of differentiation, has been the rule.

Recent statements by the Big Three's top stylists are enlightening. Asked by Automotive News in 1978, "Do you try to be different from General Motors?", Gene Bordinat, top stylist at Ford responded:

As a matter of fact, we have enough G-2, as they do, to know what they're doing, frequently not early enough for us to do anything about it. We strive not to be like them and not to be too far from them. It's an interesting balance. They do the same thing.³⁶

In another interview, Automotive News asked the head stylist at Chrysler, Richard G. Macadam, "Whom do you rate among your chief competition?"

A. I don't worry a lot. I certainly maintain a very careful and complete awareness of General Motors. You just can't ignore them with 55, 56, 57 percent of the market.

If they introduce something that deviates from the norm at all, they're going to saturate the market with it in one year flat, and it's going to have a significant effect and influence on people's perception and values and taste in automotive products. So we've got to be extremely aware of what they're doing. When Bill Mitchell makes statements about his leadership, it's not just his leadership, it's the corporation's leadership. It's their ability to saturate.

Q. Will Dick Macadam and Chrysler Design spring any surprises on the industry in the next few years? Do you have anything up your sleeve?

- A. Oh, I guess I do. I wouldn't want to disappoint the public. We'll keep everybody alert. G.M. needs an occasional challenge and we'll do what we can.³⁷

It is noteworthy that Bill Mitchell, in charge of G.M.'s styling between 1958 and 1977, placed considerably less weight on the designs of his competitors. "I would never copy an American car," he once said. "I would be embarrassed."³⁸ Nor was the self-confident Mitchell any more enthusiastic about consumer surveys as a guide to new styling: "I have contempt for surveys. I've told everybody from Donner (G.M. president during the late fifties) on down, 'Why ask people what they like when they don't know what the hell they want?'"³⁹

As these statements imply, G.M. has been the industry's product leader during the post-war period; its leadership in the product area, moreover, appears as consistent as in the setting of prices. G.M. has initiated most of the major changes in car design over the last thirty years. These changes include the introduction of high-compression V-8 engines, stylistic features such as tail-fins and wraparound windshields, the introduction of compact and intermediate-sized cars, changes in the pace of styling modifications, the catalytic converter, the "downsizing" of cars in the 1970's, and the introduction of diesel engines. More often than not, the lesser firms have followed G.M. or have been careful not to differ very much from the leader's policies. As a result, a pattern of parallel product development has emerged.

This parallelism goes beyond that of an unconcentrated industry where firms react in a similar way to change in market conditions. In the mature oligopoly, parallel behavior has the added dimension of avoiding the lower profits and greater uncertainty of unrestrained competition. That parallelism has lessened uncertainty in the industry is shown by the fact that since the adoption of a common product policy in the 1950's, there has been no significant shift in the relative market shares of the Big Three.

As a result, product parallelism reduces the demand for new technology. Imitation calls for the restraint of counter-innovation; experimentation with the unorthodox is discouraged. Moreover, collective uncertainty-avoidance urges a modest pace of technological change for the industry in general.

e. The Firm's Position in Pre-innovation Product Space

This factor refers to the relevance of the firm's sales and profits before innovation. Does G.M., for instance, have a greater incentive to innovate, and does it tend to demand more new technology than its lesser rivals because of its superior revenues and profitability?

Obviously, G.M. spends more on R&D than its rivals, and this may be a result of high revenues and profits. However, some expenditures are due to the larger number of car lines that G.M. carries; to some extent, each line requires separate development. Therefore, it is necessary to look at G.M.'s R&D on a relative basis. Table 3

presents R&D figures as a percent of sales for the domestic automakers between 1967 and 1978. Expenditures relative to sales for G.M. and Ford are nearly identical, while those of Chrysler and American Motors are much less.

A correction must be made for differences in vertical integration. That is, the amount of new technology that goes into the cars of the smaller, and less integrated, firms tends to be understated by R&D as a percent of sales: the smaller firms tend to rely more on vendors for components, materials, and hence for new technology; their larger rivals do more of their own component development. This being so, R&D figures as a percent of value added are required; these data are presented in Table 4.⁴⁰

Table Four defies easy interpretation. If size and profitability encourage innovation, it would be expected that R&D as a percent of value added (R&D/VA) would be greatest for G.M., somewhat smaller for Ford, and smaller still for Chrysler and A.M.C. This pattern is not observed: over the period, R&D/VA for Ford averaged higher than that of G.M.'s; and in recent years, Chrysler's R&D/VA has exceeded G.M.'s. Moreover, it is unfortunate that except for one year, 1974, the figures for A.M.C. are not strictly comparable with those of the larger firms. In short, the data do little to encourage the hypothesis that sales and profitability tend to increase the firm's demand for new technology and its inclination to innovate.

TABLE 3
R&D Expenditures as a Percent of Sales

Year	G.M.	Ford	Chrysler	A.M.C.
1967	3.3	3.1	1.2	--
1968	3.1	2.5	1.1	--
1969	3.2	2.8	1.3	--
1970	4.3	3.0	1.2	--
1971	3.2	3.1	1.1	--
1972	3.1	3.1	1.3	--
1973	3.0	3.6	1.3	--
1974	3.4	3.6	1.4	1.9
1975	3.1	3.1	1.7	1.6
1976	2.4	3.2	1.8	1.7
1977	2.6	3.1	1.7	1.9
1978	2.6	3.4	2.5	1.9
AVERAGE	3.1	3.1	1.5	1.8

Sources: Chrysler Corporation, "Request for Suspension of the 1977 HC and CO Emission Standards," January 1975; Ford Motor Company, "Application for Suspension of 1977 Motor Vehicle Exhaust Emission Standards," January 1975; General Motors Corporation, "General Motors Request for Suspension of 1977 Federal Emission Standards," January 1975; Annual Stockholders Reports, 1976-1978.

TABLE 4
R&D Expenditures as a Percent of Value Added

Year	G.M.	Ford	Chrysler	A.M.C.
1967	6.3	7.8	3.0	--
1968	6.0	5.9	2.6	--
1969	6.4	6.8	3.4	--
1970	8.6	7.0	3.1	--
1971	6.1	7.1	3.7	--
1972	5.9	7.2	4.0	--
1973	5.4	8.3	3.1	--
1974	7.2	9.5	3.8	5.6
1975	6.6	8.4	6.4	6.1*
1976	5.4	8.0	6.3	6.2*
1977	5.3	6.6	5.0	6.6*
1978	5.3	8.8	7.6	6.4*
AVERAGE	6.2	7.7	4.4	6.3*

*Not strictly comparable with other figures

Source: Same as Table 3

However, it is clear that high cash flows give discretion to managers. Ultimately, the decision to spend an extra dollar on R&D or to give it to stockholders depends on the preferences of stockholders on dividends today versus dividends tomorrow; these preferences are largely influenced by rates of return on alternative investments. It is possible stockholders exhibit diminishing marginal utility on dividends today in the sense that after more and more dividends are paid out, it becomes easier for management to hold back a sum that can be devoted to R&D.

As a result of higher profits, G.M., and to a lesser extent Ford, have been less constrained than Chrysler and A.M.C. in setting R&D expenditures. It is not surprising that Richard Terrell, vice-chairman of General Motors, denied that there is any fixed percent of revenues which is automatically assigned to R&D. Instead, Mr. Terrell insists that the amount of money that goes into R&D "evolves from the effort we want to put forth."⁴¹

In contrast are the following testimonies of the president and chief engineer of Chrysler; note the emphasis on economy and necessity:

Mr. Riccardo: I want to clarify an issue of money here today because our figures will not be very dramatic when compared to General Motors.

But, Senator, this has been our life all along. We have never spent the money in engineering and research that either Ford or General Motors has done. We don't believe that money alone solves problems. I think the Federal Government can prove that.

It is our position that we have more innovations in the field of emission controls and we have as many or more than our share of innovations in any engineering part of the automobile than our competitors.

We have done that, Senator, with very restricted budgets compared to them. We don't make anywhere near their profits. Obviously we cannot afford to apply the same resources, but a comparison of dollars in the cold light of day does not tell the story. We have to be emphatic about that point. We get a lot for our money Senator, I would like my top engineer who runs my engineering department to speak on the adequacy of what he thinks his budget is.

Mr. Loofbourrow: It has always been my experience with the operation at Chrysler Engineering that the corporation has been very liberal in supplying funds for what we feel is necessary to get the technical work that we need to do.

As Mr. Riccardo has indicated, because of the differences in profits and size we have had to, over the years, use a different engineering approach. You don't have to be real good technically to build samples of every idea that comes along and try it and find it won't work.

This takes a better engineering technical skill to do this. It takes a lot of self-confidence as well. This is our lifeblood. It is how we stay competitive. We have done this over the years. We have looked at every alternative or modified engine that anyone has suggested.

These suggestions that come in literally are hundreds. We have looked at every one. We make math models of some of them to find out how they run, run them through the computer.

This is an economical way of doing it.⁴²

Were it not for indivisibilities in the introduction of new technology (i.e., progress comes in the form of "chunks" of techtills called innovations), profits and revenues would be of little consequence. If indivisibilities were absent, even tiny firms, with limited financial resources, could afford the cost of entry (the

price of one techtil) into new product space. While this is not the case, it is a mistake to jump to the complementary conclusion that firms with large revenues and profits are "an almost perfect instrument for inducing technical change."⁴³ While the ability to overcome indivisibilities plays a role in determining the firm's demand for new technology, the willingness of the firm to accept uncertainty is as critical.

6. Equilibrium Output of New Automotive Technology

In any market, equilibrium price and output are determined by the interaction of demand and supply. So too in the case of new automotive technology. The extension of supply and demand analysis to new technology involves a higher degree of abstraction in comparison to the analysis of well-defined markets such as wheat or gasoline. The unit to measure technology is imaginary, the "price" for new technology is apt to be invisible, and the nature of supply is probabilistic. Nevertheless, the extension of supply and demand analysis to new technology is helpful since the factors that affect the output of new technology can be clearly indicated.

Activity in the market for new automotive technology does not have the impersonalness of perfect competition. In any given direction of new automotive technology, there are too few sellers and certainly too few buyers to satisfy the conditions of perfect competition. Therefore,

modifications of the model are required to take market power into account.

While there may be occasions of bilateral market power, the bulk of the bargaining power is on the side of the technology-buyers, i.e., the automakers. This power is based on the high concentration in automobile production and high barriers to entry. Since a unit of new automotive technology has no value until embodied in the final product, firms that produce the technology must turn to the automakers.

With respect to vendors, the automakers can threaten to stop or reduce purchases of existing components and raw materials if new technology is not supplied on favorable terms. It is noteworthy that a Ford vice-president in charge of purchasing once stated that "Ford suppliers receive constant encouragement from the company's purchasing activity to step up their R&D programs Suppliers who maintain progressive R&D activities and who contribute to the improvement of Ford products are the suppliers most frequently asked to bid on the company's requirements."⁴⁴

The threat to withdraw sales is serious, since a vendor may not be able to offset the loss quickly by sales to another automaker. Moreover, since the Big Three are integrated backwards into the production of not a few components and materials, the potential substitution of in-house production further enhances the automakers' leverage; this backward integration also extends to technology

production itself. To be sure, the automakers may have more bargaining power with some vendors than others and, over time, the relationships may change. However, in general, this is a case of monopsony--or more precisely, oligopsony--where the buyer(s) can sway the terms of trade to their own liking.

As Figure 6 illustrates, theory predicts a restriction of output with monopsony as compared to the competitive case; the monopsonist increases his profits at the expense of sellers by forcing a lower price than would occur under competitive conditions. As a result, sellers reduce output.

It is suspected that there is a second effect of monopsony power in this particular case. By tying the purchase of current inputs to the production of new technology, the automakers may be able to force the vendors' supply of new technology to the right. Vendors are often eager to conduct R&D to keep good relations with the automakers; they are apt to view technology production as a form of non-price competition instead of a line of business in itself. This is not to say the effect of a restricted quantity supplied due to a monopsony price is absent: it and the supply-increasing effect may both be present.

Figure 7 illustrates. S' represents the new technology supply curve for vendors under the assumption that supply-increasing effect is present. While in Figure 7 the equilibrium output is less than that predicted for competitive conditions, this may not be true:

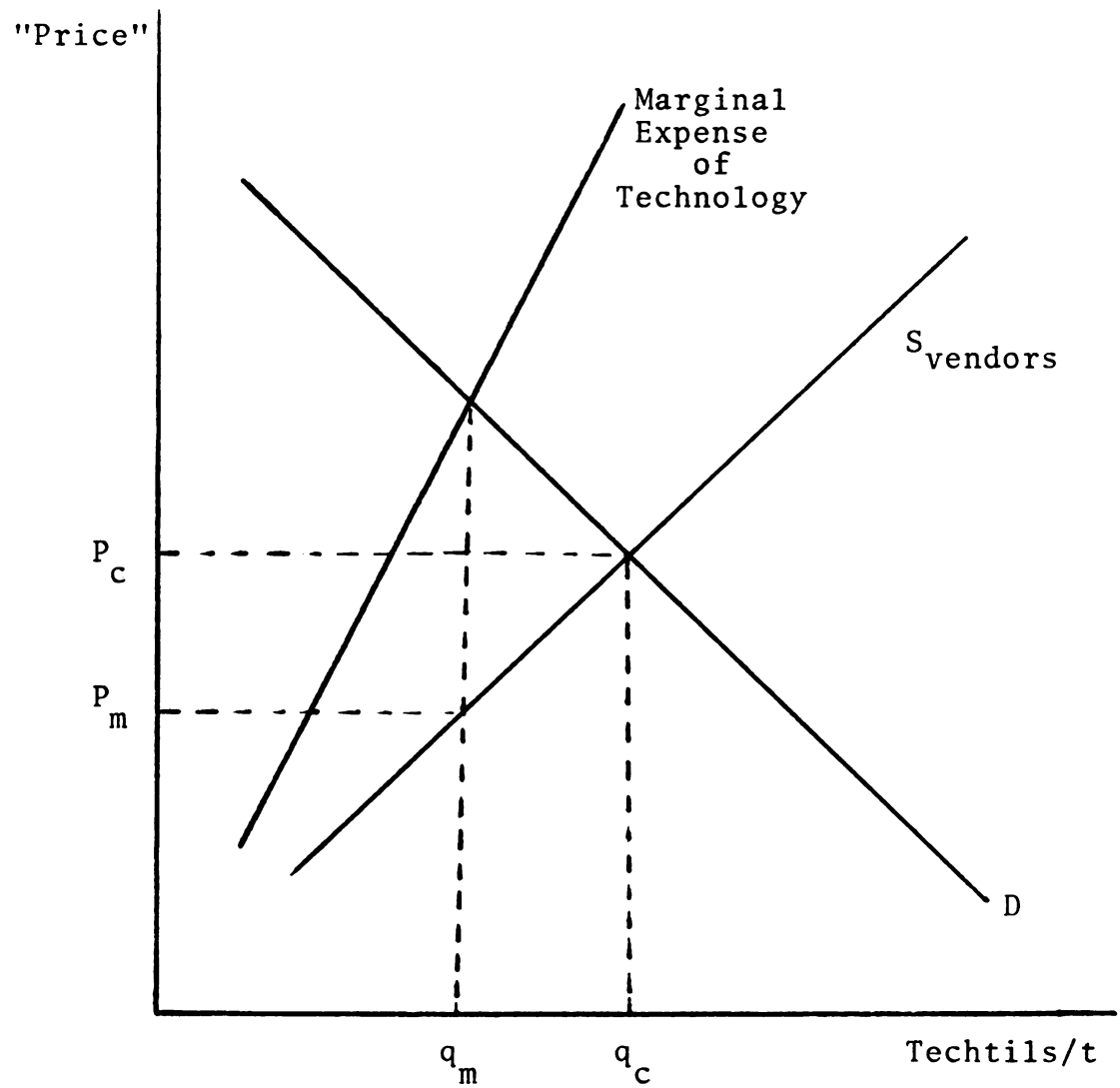


FIGURE 6

Output-Depressing Effect of Monopsony

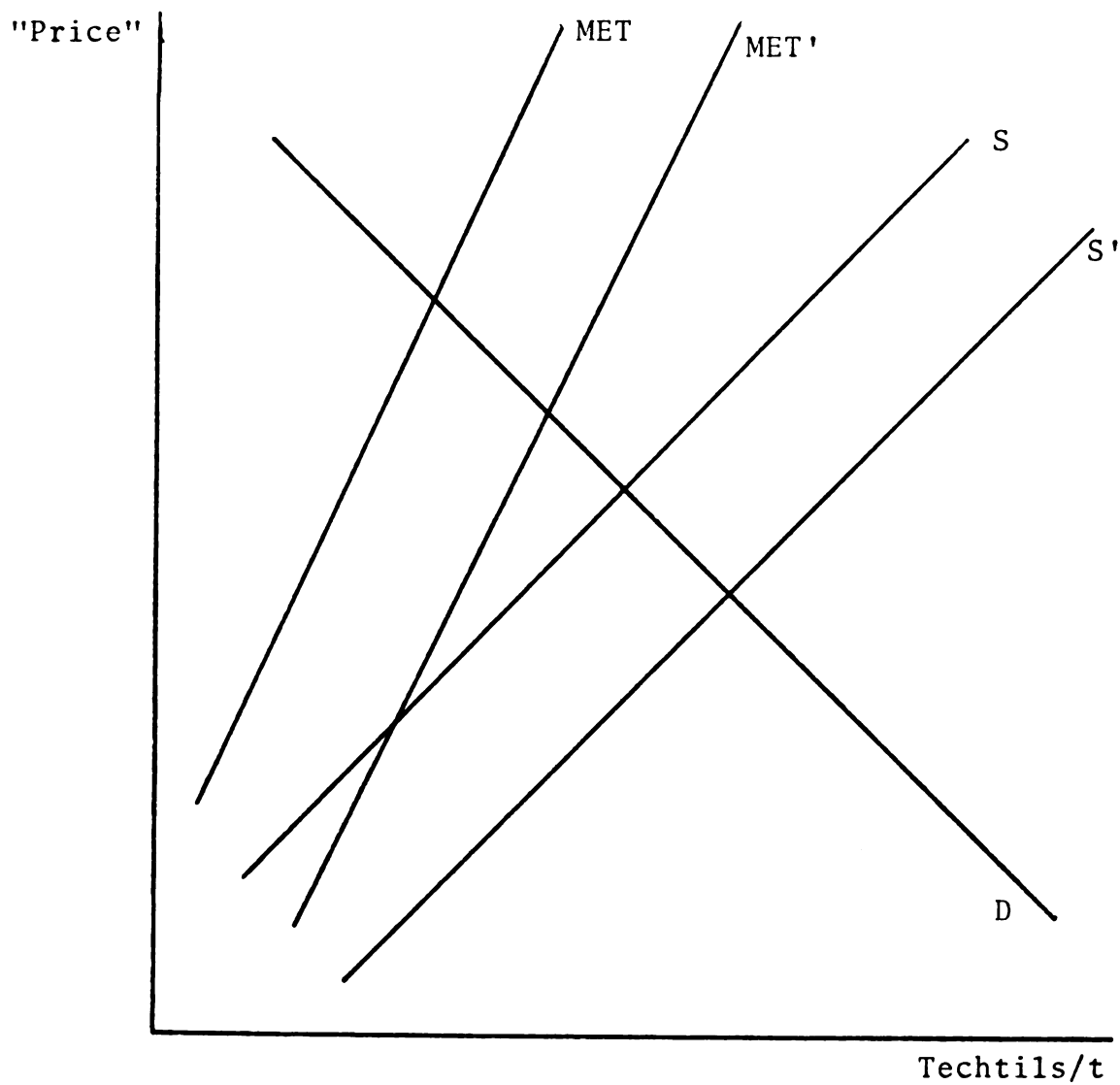


FIGURE 7

Output-Increasing Effect of Monopsony

conceivably, S' could be much more to the right than pictured. Also note that if the automakers use their bargaining power to drive down the price of new technology, this, by itself, continues to restrict the quantity supplied.

Figures 6 and 7 represent the pure monopsony case. To the extent that the market power is weakened by there being several instead of one buyer, or due to countervailing power on the sellers' side, the equilibrium output of new technology from vendors is apt to be closer to competitive level.

If the automakers' market power shifts the technology supply curves of vendors to the right, the total supply of new automotive technology increases by the same amount. However, it is also possible the automakers, to at least some extent, merely substitute the R&D work of vendors for that of their own R&D departments. A strong incentive to do so is the shifting of the uncertainty of technology production to the vendors; this would be consistent with the automakers' aversion to risk. This substitution may be so extensive that any increase in the technology supply of vendors is completely offset by a lessening of effort by the automakers.

Whether the automakers have a similarly decisive power in dealing with inventor-firms is not clear. On the one hand, inventor-firms, unlike vendors, are not threatened by the loss of current sales. On the other, barring entry into the product market, the inventor-firm must sell

its technology if a profit is to be made. If an inventor-firm has an economic monopoly on a new concept and secure property rights, it is conceivable that even if the firm faced a small number of buyers, it could secure the monopoly price. Still, concentration on the buyers' side could force a lower price, especially if there was collusion.

Is there collusion among automakers to keep the price of outside inventions down? Unfortunately, evidence on this matter is scanty. One case of overt collusion to control competition in the acquisition of pollution-control patents and licenses occurred during the 1950's and 1960's. A document of the Automobile Manufacturers Association, dated May 10, 1954, stated:

Heinen [of Chrysler] asked whether a company coming across a satisfactory device either submitted by an inventor, developed during the course of normal company research, or during the course of (VCP) Subcommittee studies should make the device and its details known to the other companies participating in the Subcommittee work. The alternative, of course, would be for the company to say nothing and then "scoop" the other manufacturers with an anti-smog device. In view of the common importance of the smog problem to all of the companies and in view of the satisfactory cooperative nature of the work thus far, the individual company approach was not generally favorable. However, it was recognized that very serious legal problems might be involved in the cooperative acceptance and review of devices.⁴⁵

The threat of antitrust prosecution did not deter the automakers from adopting a cross-licensing agreement in April, 1955. This agreement required royalty-free cross-licensing of six categories of devices; in addition the firms agreed to share the cost of obtaining patents from outsiders; a "favored nation" clause was also included, in

which outsiders were forced to license all members to the agreements at the same royalty rate. These provisions eliminated competition in the purchase of inventions. This anticompetitive arrangement remained in effect until challenged by the Justice Department in 1969.

This episode no doubt is an exceptional case. But an exception from what? Perhaps it was an overt expression of normally tacit collusion; or possibly the norm is fairly vigorous competition.

Ralph Nader, to whom many small-time inventors have turned, believes the auto companies are not eager for the ideas of outsiders:

As far as the consideration of outside technology is concerned, the domestic manufacturers will not review the disclosure of unpatented technology unless the inventor signs a submission agreement which negates any potential obligation of the manufacturer. Many inventors are completely frustrated by this artificial barrier to technological consideration and innovation, and refuse to cooperate further with auto manufacturers. Copies of inventor correspondence showing this fact are submitted for the hearing record along with a staff memorandum analyzing this correspondence.

Obviously most of these inventors are warded off with being told that this has to clear the offices of legal counsel first. The road to technological feasibility is not through the doors of legal counsel. Even when legal counsel is involved, inventors who have progressed this far are frequently given such short shrift that the principles of the invention are not even understood by the representatives of the auto industry evaluating the invention.⁴⁶

Nader also points to a General Motors pamphlet that states G.M. "does not solicit ideas" or "does not in any way ask people to make submission."⁴⁷

G.M. maintains that this language is required for legal reasons, and is not designed to choke off the contribution of outside inventors:

It is essential to protect the public and General Motors, that the legal rights and obligation associated with technological suggestions be defined accurately at all stages of the procedure. Some legal decisions have suggested that solicitation of suggestions by a business concern creates some obligation to make payment therefore. It is impossible for General Motors to know the worth of any suggestion in advance of its submission and it cannot incur such obligations. Therefore, to avoid any possible contention that General Motors is soliciting technological suggestions, the formal papers associated with submission of such suggestions affirmatively state that General Motors does not solicit ideas or ask people to make suggestions.⁴⁸

It is not clear whether submission agreements are anticompetitive devices or are merely an unfortunate drawback of our legal system. The author is inclined to support the latter view.

7. Possibilities for Technological Suboptimization

Now consider suboptimization in automotive technology.

a. Type I Suboptimization

Type I suboptimization occurs when more than a necessary minimum of resources are sacrificed to produce a given amount of new technology. The major cause of Type I suboptimization is insufficient competitive pressure.

As far as the automotive vendors are concerned, Type I suboptimization seems unlikely. Competition among vendors for sales to the automakers is strong; the production of new technology by vendors is used to maintain current sales

and to promote future ones. Moreover, the market power of the automakers probably enforces the vendors' efficiency in the production of new technology.

Type I suboptimization by inventor-firms also seems unlikely or trivial. Inventor-firms must be quick to produce patentable new technology if a profit is to be made; the number of inventor-firms and the relative ease of entry in the production of unrefined new technology would seem to discourage inefficiency. Furthermore, the market power of the automakers may also force inventor-firms to be efficient.

The R&D departments of the automakers, however, are subject to less pressure than either vendors or inventor-firms and this makes Type I suboptimization more likely. After all, they represent "captive plants" of their firms' car-producing divisions, and may have less incentive to sell their ideas to these divisions than outsiders.

Unfortunately, it is difficult to reach a firm conclusion about Type I suboptimization at the auto companies. It is interesting to note, for instance, that during recessions the automakers tend to cut their R&D budgets: this may indicate a tightening of cost-controls in R&D programs. On the other hand, the cutbacks may not mean an increase in efficiency but a reduction of marginally important research projects. Another factor is the internal competition in the firms' R&D departments: this may be strong enough to enforce efficiency. In short, more information is needed.

Finally there is the matter of "defensive" research and development. Defensive R&D is defined as technology-production whose purpose is to protect the firm's future market position from potential entrants or to put the firm in a more favorable bargaining position in the purchase of new technology. To the extent that defensive R&D merely duplicates the units of technology already produced by others, it is, from the social point of view, wasteful, and is a form of Type I suboptimization. Nevertheless, R&D work whose supposed object is merely defensive may fortuitously result in socially useful technology. And the defensive R&D of a firm puts pressure on challengers and, as a result, forces them to invent efficiently.

Defensive R&D is not uncommon in the auto industry. For example, some of the automakers' efforts to develop the catalytic converter appeared to be defensive. One official of Universal Oil Products, an early leader in the development of catalytic devices, complained in 1971 that the automakers were largely duplicating the work already done by his firm. "This is traditional with Detroit," he said. "They want to have their own in-house solutions to problems if they can. They don't like to have one source of supply for anything. Detroit is stalling to see if they can do in a couple years what took us a decade to do."⁴⁹

In short, if Type I suboptimization exists in the automotive technology market, it is most likely associated with the automakers since their R&D departments appear less

subject to competitive pressure than other technology producers. Also, Type I suboptimization may be more prevalent at the more profitable firms because there is more room for organizational slack; admittedly, this may be putting the cart before the horse in the sense that higher profits may be the result of better cost control. Finally, Type I suboptimization may be present due to purely defensive R&D activity.

b. Type II Suboptimization

Type II suboptimization is zero when the vector of technology production and use is such that no other vector results in a greater increase in social net benefits.

Assume (1) that time is divided into two periods, "present" and "future"; (2) that the costs of producing new technology and setting up for its use are incurred in the present; (3) that the benefits of innovation are not realized until the future; (4) that the vector of technology production and use is one-dimensional, i.e., technology is homogeneous; (5) that externalities are absent; and (6) certainty prevails.

The addition to social net benefits due to innovation is equal to the change in consumer surplus plus the change in producer surplus. Depending on the underlying social welfare function, the division of the new social net benefits may be important. Assume, however, that society is indifferent to how the division is made; that is, social

welfare remains unchanged if a dollar of consumer surplus is transformed into a dollar of producer surplus.

In such a world, the rate of technology production and use, T , is optimal if the present value associated with that rate, given by

$$(1) \text{ PV} = \frac{f_c(T) + f_p(T)}{(1 + r)} - C(T),$$

is a maximum. Here $f_c(T)$ and $f_p(T)$ represent the change in consumer and producer surpluses due to the introduction of new technology; $C(T)$ is the total cost of technology production and set-up; r is a time rate of discount.

Moreover, $C'(T)$ is greater than zero with $C'(T) \rightarrow \infty$ as $T \rightarrow \infty$. It also is reasonable to assume that after some point the change in surpluses becomes subject to diminishing returns, i.e., $f'_c(T)$ and $f'_p(T)$ become small, and perhaps, even negative. As Figure 8 illustrates, these conditions imply a socially optimal rate of technology production and use, denoted by T^* .

Whereas the social calculation must include both producer and consumer surpluses versus cost, the private calculation includes only the producer surplus. The firm seeks a rate of technology production and use which maximizes the value of

$$(2) \text{ PV}_i = \frac{f_{pi}(T_i)}{(1 + r)} - C_i(T_i).$$

Here f_{pi} and $C_i(T)$ are the producer surplus and new technology cost functions for the individual firm; T_i is the new technology introduced by the firm.

The socially optimal rate of technology production and use requires that $\sum_{i=1}^n T_i = T^*$, where n is the number of innovating firms.

It is clear that if a firm enjoys a monopoly in the use of new technology ($n = 1$), the rate of technology production and use is less than T^* . Unless the monopolist is able to impose a costless form of perfect price discrimination, some part of the social net benefits will escape and emerge as consumer surplus. As a result, the equilibrium rate of technology production and use, when the end-use is controlled by a monopolist, is less than the socially desirable rate T^* ; denote this monopoly rate as T_m .

Compare this outcome with that associated with competition, i.e., $n \geq 2$ and with no collusion. While a monopolist must take into account the impact of an innovation on the profitability of his other ones, the competitor does not care if an innovation has the effect of reducing the profitability of rivals. Innovations that are substitutes are apt to be offered by the various firms; competition of a familiar nature takes place with the result that producer surpluses fall while consumer surpluses rise. Unlike the technology-monopolist, firms in competition are unable to profit from a contrived scarcity of technological alternatives; the rate of return on the

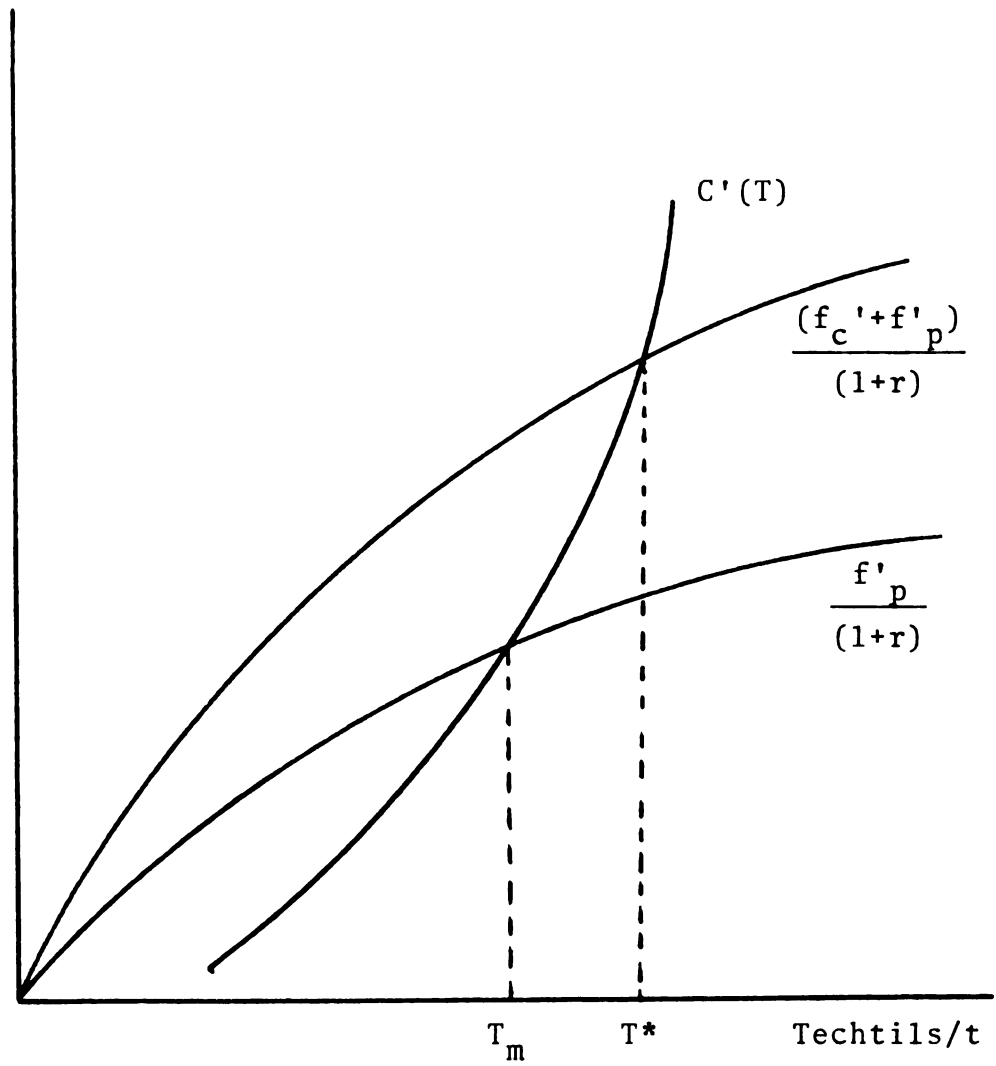


FIGURE 8

Socially Optimal Rate of Technology
Production

investment in new technology for each firm will tend to be smaller than that of technology monopolist. While the contribution of the individual firm may be smaller as a result of this lower rate of return, the total contribution of firms under competition, T_c , will be greater than T_m .

But will T_c equal T_i^* , the socially optimal rate? Or, in other words, if competition cuts the rate of return to some minimum, is that rate a satisfactory incentive for the introduction of T^* units of new technology per unit of time? The answer is no. The private calculation on innovation, even under competition, is still based on only part of the new net social benefits of innovation, viz., the producer surplus which the firms are able to capture. The firm will find it worthwhile to innovate as long as this competitive rate of return is not less than the opportunity cost of investing in new technology which is equal to the present rate of return in the capital market. This being so, the market system, even under the most ideal conditions, will under-allocate resources to technology production and use.⁵⁰

The situation becomes more complex when the assumption on certainty is relaxed. Professor Arrow has concluded that while "the economic system has devices for shifting risks" . . . "they are limited and imperfect; hence, one would expect an underinvestment in risky activities." Professor Arrow adds that "risky business activities, including invention . . . should be undertaken if the

expected return exceeds the market rate of return, no matter what the variance is." . . . "Hence any unwillingness or inability to bear risks will give rise to a non-optimal allocation of resources, in that there will be discrimination against risky enterprises as compared with the optimum."⁵¹

In short, uncertainty creates a tendency for the market system to underallocate resources to risky ventures. The rate of new technology production and use is apt to be less than the socially optimal rate. Furthermore, if uncertainty-avoidance is an argument in managerial utility functions, and if collusion among firms is feasible, the degree of suboptimization is increased.

Another factor deserves attention: the socially optimal time-rate of discount. Firms make a comparison between the rate of return on innovation and the present market rate of return. Although suboptimization may already be present due to uncertainty, it may be worsened if the market rate of return is not the same as the social rate of discount. There is no reason to assume that the market rate of return is identical to the social rate of discount.⁵²

The determination of the social rate of discount requires a political judgment. If the social rate of discount is lower than the present market interest rate, the implication is that the production and use of new technology is lower than socially optimal. Technological

opportunities with net social benefits would exist, but with returns too low to justify private exploitation.

Finally, Type II suboptimization will result if externalities are present. There may be spillover benefits which the firm cannot appropriate: this is a "free rider" problem. There may be negative externalities due to technology production and use. If spillover benefits are present, there will be a tendency for too little technology production and use; if negative externalities are present, the opposite is true.

What are the possibilities for Type II suboptimization by the automobile industry? Obviously, what can be said about any industry applies here. Externalities in the production and use of automotive technology will not be taken into account by firms; a discrepancy between the rate of returns used by firms and the social discount rate causes a further distortion. The inability to capture all of the new net social benefits due to innovation results in further suboptimization.

In the market for automotive technology, moreover, Type II suboptimization may be present due to the market power of the buyers. It is possible that a monopsony effect is at work which results in a less than socially optimal rate of technology production; the monopsony effect, however, may be offset by a supply-increasing effect.

Uncertainty-avoidance product collusion by the automakers may be an important cause of Type II suboptimization.

The lesser firms tend to follow the product leader, G.M.; in the interest of stabilizing market shares, tacit imitation rather than truly differentiated product policies is the rule. As a result, the production and use of new automotive technology falls short of the socially optimal rate.

c. Type III Suboptimization

Type III suboptimization is the neglect of already produced technology which could increase social welfare. Type III suboptimization occurs when the profit incentive fails to perform its socially desirable role in promoting innovation.

Four causes of such a failure can be identified. First, information about invention may fail to reach potential innovators.

Second, a commitment to older technology may encourage a firm to block the entry of new technology into the marketplace.

Consider this hypothetical example. A firm sells good X. Its research department comes up with a new good that in some respects is a superior substitute for X. The firm's econometrician reports that, although there would be a demand for the new good, introduction of it would reduce the demand for the firm's old product: consequently, no increase in profit can be expected. Upon hearing the report, the firm's managers decide that innovation is not worth the trouble, at least at the moment.

The decision results in Type III suboptimization. Although the firm would be no better off, the welfare of at least some buyers would have risen with the offering of the new product. Note that the firm would have had the incentive to innovate were it not for the commitment to the older technology.

A third possible cause of Type III suboptimization is collusion. A firm may hold back on innovation out of fear of retaliation by rivals; collusive agreements may replace independent decision-making in determining the timing of innovation.

A fourth possible cause of Type III suboptimization has to do with the organization of the firm: this may be called the bureaucratic inertia hypothesis. A large and complex corporate structure may make it difficult for a firm to be an innovator. While the extreme division of labor and democratization of decision-making may be admirable qualities in dealing with the status quo, they may very well discourage change. Bureaucratic inertia may prevent the firm from quickly exploiting the possibilities opened up by invention: in other words, the organization of the firm may preclude long-term profit maximization.

The available evidence suggests that collusion and bureaucratic inertia deserve special attention. A blatant example of Type III suboptimization due to collusion occurred with the development of pollution control devices during the 1960's. As early as 1960, Chrysler had

perfected a system, the Cleaner Air Package, which could meet the demands of California state law. In a memo dated October 5, 1961, a Dupont executive asked a high-ranking Chrysler engineer why his firm did not seek certification of the Cleaner Air Package in California:

While admitting that favorable publicity would result, he was very forceful in telling me that if this was done Chrysler would be severely chastised by the rest of the industry. He reminded me that the AMA agreement says no one company will gain any advantage because of smog, and that Chrysler was a relatively small cog in the industry. He indicated Ford and GM were calling the shots and implied that Chayne [GM vice president] was the industry mastermind."⁵³

Although Chrysler nearly struck out on its own in 1964, the firm eventually bowed to industry pressure and joined G.M. and Ford in asking California to delay mandatory installation of pollution control systems until the 1966 model year. Ironically, G.M. and Ford eventually adopted the concepts pioneered in the Cleaner Air Package.⁵⁴

There is stront testimony to support the bureaucratic inertia hypothesis. One early student of the industry concluded that the small auto firms of the 1920's were not always at a disadvantage in competing with their larger rivals:

While it is true that the large firm can maintain more elaborate experimental laboratories than the small, it does not follow that the capacity for profitable decision as to what changes to make in the product, and the time to inaugurate them, are in any way the peculiar property of the large corporation. The very fact that the enterprise is large may sometimes hamper the initiation of these alterations in product and policy. In other words, "progressiveness," or what passes for it, in such an industry is not necessarily a function of size.⁵⁵

It is noteworthy that Alfred P. Sloan, of G.M., expressed a similar opinion:

In practically all our activities we seem to suffer from the inertia resulting from our great size. It seems too hard for us to get action when it comes to a matter of putting our ideas across. There are so many people involved and it requires such a tremendous effort to put something new into effect that a new idea is likely to be considered insignificant in comparison with the effort it takes to put it across.

I can't help but feel that General Motors has missed a lot by reason of this inertia. You have no idea how many things come up for consideration in the technical committee and elsewhere that are agreed upon as to principal well in advance, but too frequently we fail to put the ideas into effect until the competition forces us to do so. Sometimes I am almost forced to the conclusion that General Motors is so large and its inertia so great that it is impossible for us to really be leaders.

Perhaps it would be safest for us to let the other fellow take the initiative and then be satisfied to follow him as best we can. It seems a pity, however, that with our resources and ability we can't be a little more aggressive.⁵⁶

Despite modern managerial techniques, the problems which Mr. Sloan worried about in 1925 may still bedevil G.M. in the 1970's. Such is the view of John Z. DeLorean, who in 1972 unexpectedly resigned his position of executive vice-president at G.M. Like Sloan, DeLorean complained of the unresponsiveness and unwieldiness of G.M.'s vast corporate structure:

"You were getting all your input from lower-level specialists," he says. "They provided information in such a way that they would get the answer they wanted. I know, I used to be down below and do it. The feeling I started to get, being suddenly put on the fourteenth floor, was that now I was being presented with information that had limited alternatives. This is totally inconsistent with any thoughtful and creative originality. You never could reflect on and modify a proposal. You couldn't be a planner. You were too

harassed by committee meetings and paperwork--you just had tons of it. You were cut off from the outside world. You saw only the men on the fourteenth floor. The corporate hierarchy was just reacting to the demands of the organization and responding to some degree to the government and the public. It was like standing in the boiler room and tending a machine and you were just watching it instead of running it."⁵⁷

The implications of bureaucratic inertia at General Motors are especially significant in view of that firm's role as industry product leader.

NOTES

1. National Science Foundation, Federal Funds for Research, Development, and Other Scientific Activities (Washington: U.S. Government Printing Office, 1966), p. 9.
2. Ibid., p. 14.
3. Ibid., p. 19.
4. Jet Propulsion Laboratory, Should We Have a New Engine?, 2 vols. (Pasadena: California Institute of Technology), 2: 15-2.
5. P. M. Heldt, Torque Converters or Transmissions (Philadelphia: Chilton Co., 1955), p. 18.
6. The electric starter was invented by Charles Kettering's Dayton Engineering Company in 1911; an important improvement in the electric starter, the Bendix drive (1913), was the first of many automotive innovations coming from the company of the same name. The Budd Co. of Philadelphia developed the first all-steel body in 1914. The first cheap colored lacquer, Duco, was largely developed by Dupont (1923). Gleason Works was responsible for the introduction of hypoid gears (1926). Automatic overdrive was developed by Borg-Warner (1934) while the vacuum-powered clutch was introduced by Bendix (1932). The Budd Company perfected the unitary body construction which was first used by Nash in 1940. For other early automotive inventions by vendors, see Ralph C. Epstein, The Automobile Industry (New York: A. W. Shaw Co., 1928), p. 17.
7. U.S. Congress, Senate, Committee on the Judiciary, Subcommittee on Antitrust and Monopoly, Hearings on Administered Prices, Automobiles, 85th Congress, 2nd Sess., 1958, p. 2878.
8. U.S. Environmental Protection Agency, Automobile Emissions Control (Washington, U.S. Government Printing Office, 1975), pp. 7-34.
9. J. H. Hunt, "Opportunities in Design and Research in Automobile Engineering," Journal of the Society of Automotive Engineers 22 (May 1927): 592.
10. Lawrence J. White, The Automobile Industry Since 1945 (Cambridge, MA: Harvard University Press, 1971), p. 212.

11. An exception is the oil companies whose officials keep in close contact with counterparts in the auto industry. Because of the close relation between fuels and engines, the oil companies have long been active in the development of better automobile engines.
12. Detroit Free Press, May 5, 1978, p. 43.
13. Business Week, June 28, 1976, p. 67.
14. Alfred P. Sloan, My Years with General Motors (Garden City, NY: Doubleday and Co., Anchor Books ed., 1972), p. 289.
15. Ibid., p. 297.
16. Interview with officials of the General Motors Corporation, August 28, 1975.
17. Ford Motor Company, "Application for Suspension of 1977 Motor Vehicle Exhaust Emission Standards," January 1975, section XI, p. 14.
18. Chrysler Corporation, "Request for Suspension of the 1977 HC and CO Emission Standards," January 1975, section II-A, pp. 36, 38.
19. Jet Propulsion Laboratory, op. cit., 2: 15-2, 15-3.
20. U.S. Congress, Senate, Committee on Public Works, Hearings on the Decision of the Administrator of the EPA Regarding the Suspension of the 1975 Auto Emission Standards, 93rd Cong., 1st sess., May 1973, pp. 1330-1; also see U.S. Congress, House, Subcommittee on Space Science and Applications of the Committee on Science and Astronautics, Hearings on Research on Ground Propulsion Systems, 93rd Cong., 2nd sess., June 1974, p. 445.
21. Gregg Condaeracci, "Edward Cole May Be Last of Dying Breed in Automotive World," Wall Street Journal, Feb. 5, 1974, p. 1.
22. Sloan, op. cit., pp. 269-270.
23. Maurice Olley, "Comparison of European and American Automobile Practice," Journal of the Society of Automotive Engineers 16 (August 1921): 111.
24. The car was the Volkswagen Rabbit equipped with diesel engine. See U.S. Environmental Protection Agency, 1979 Gas Mileage Guide.

25. For a more complete account of this period see Ralph C. Epstein, "The Rise and Fall of Firms in the Automobile Industry," Harvard Business Review 5 (January 1927): 157-174.
26. L. H. Seltzer, A Financial History of the American Automobile Industry (Boston: Houghton Mifflin Co., 1928), pp. 32-33.
27. On the instability of market shares during the formative era see Ralph C. Epstein, "Leadership in the Automobile Industry," Harvard Business Review 5 (April 1927): 281-292.
28. It is interesting to speculate whether this is a general tendency in industry. If so, it may account for the apparently weak relation between structural and conduct variables in some industries.
29. Henry Ford, My Life and Work (Garden City, NY: Garden City Publishing Co., 1922), p. 149.
30. For details on this remarkable car see Howard S. Irwin, "History of the Airflow Car," Scientific American 236 (August 1927): 98-106.
31. See A. F. Denham, "New DeSoto Reflects Chrysler Engineering Practice," Automotive Industries 59 (August 4, 1928): 149-152; idem., "New Chrysler Laboratories Fitted with Ingenious Test Devices," 59 (July 21, 1928): 82-84; and "Chrysler Corporation Opens Two New Laboratories," Automotive Industries 83 (July 1, 1940): 8.
32. Sloan, op. cit., p. 310.
33. Ibid.
34. Ibid. Emphasis in the original.
35. U.S. Congress, Senate, Committee on the Judiciary, Subcommittee on Antitrust and Monopoly, Hearings on Administered Prices, op. cit., p. 2973.
36. Automotive News, April 4, 1978, p. 49.
37. Ibid., October 17, 1977, pp. 15, 20.
38. Detroit Free Press, October 31, 1976, p. 10.
39. Automotive News, June 27, 1977, p. 18.

40. Value added for the Big Three and, for 1974 only, for AMC is based on percent of sales revenue to suppliers. After 1975, AMC did not present such a breakdown in its reports; for 1975-1978, value added for AMC was taken as being equal to the sum of net income before taxes, employee compensation, interest, and depreciation. The author believes that this alternative calculation results in a higher VA/S figure than the other method somewhere on the order of one-half of a percent.
41. Business Week, June 28, 1976, p. 56. Emphasis added.
42. U.S. Congress, Senate, Committee on Public Works, Hearings on the Decision of the Administrator of the EPA Regarding the Suspension of the 1975 Auto Emission Standards, op. cit., pp. 1586-7.
43. John Kenneth Galbraith, American Capitalism (Boston: Houghton Mifflin, 1952), p. 91.
44. Ben D. Mills, "Ford Purchasing," Automotive Industries 140 (August 1, 1969): 23.
45. Congressional Record-House, May 18, 1971, p. 15628.
46. U.S. Congress, Senate, Committee on Commerce, Hearings on Automotive Research and Development and Fuel Economy, 93rd Cong., 1st sess., 1973, p. 94.
47. General Motors Corporation, "Submitting Ideas and Suggestions to General Motors," Detroit, 1971.
48. Letter from E. S. Starkman of G.M. to Mr. George Allen, Office of General Enforcement, Environmental Protection Agency, March 16, 1973.
49. "75 Catalyst Developed," Automotive Industries 144 (February 15, 1971): 19-20.
50. This is true under the assumption that both consumers and producers' utilities are arguments of the social welfare function. Considering the new net benefits to consumers, ceteris paribus, it is seen that this is maximized under competition. Hence, Professor Shepherd's assertion that innovation and invention are "optimized by competition." See The Economics of Industrial Organization (Englewood Cliffs, NJ: Prentice-Hall, Inc., 1979), pp. 394-395. T* is optimal under our assumptions in the sense that if the consumers were required to pay a lump sum equal to the new surplus they would otherwise enjoy from innovation, they would be just as well off as before innovation; innovating firms, and their owners, would be better off.

51. Kenneth J. Arrow, "Economic Welfare and the Allocation of Resources for Invention," in The Rate and Direction of Inventive Activity, National Bureau of Economic Research (Princeton: Princeton University Press, 1962): 611, 612, 614.
52. See Stephen A. Marglin, "The Social Rate of Discount and the Optimal Rate of Investment," Quarterly Journal of Economics 77 (February 1963): 95-111.
53. Congressional Record, House, May 18, 1971, p. 15632.
54. U.S. Congress, Senate, Committee on Public Works, Hearings on the Decision of the Administrator of the EPA Regarding the Suspension of the 1975 Auto Emission Standards, op. cit., pp. 1632-3.
55. Ralph C. Epstein, "Profits and the Size of Firms in the Automobile Industry," American Economic Review 21 (December 1931): 684.
56. U.S. Federal Trade Commission, Report on the Motor Vehicle Industry (Washington: U.S. Government Printing Office, 1939), p. 84.
57. Rush Loving, Jr., "The Automobile Industry Has Lost Its Masculinity," Fortune 88 (September 1973): 266-268.

CHAPTER III

THE STATE OF POWERPLANT TECHNOLOGY DURING THE MID-1970'S

1. Introduction

The purpose of the next two chapters is to test for technological suboptimization in the selection and development of automotive powerplants.

Type III suboptimization is considered in this chapter. The state of powerplant technology during the mid-1970's is reviewed to see if some alternative is better than the engine produced.

The next chapter studies the rate of development of alternative powerplants. The extent of Type II suboptimization is discussed and then explained in the context of the model developed in Chapter Three. A discussion of the extent of Type I suboptimization is also offered in the next chapter.

2. Technical Descriptions of Alternative Automotive Power-Plants

In this section, descriptions of the various powerplants are presented.

a. The Conventional Otto

This is the standard automotive engine that has been mass-produced for over seventy years. It is an internal combustion engine, which means that kinetic energy is obtained by the expansion of a chemical explosion that directly pushes a piston. In the conventional Otto, the explosive charge is a uniform mixture of air and gasoline, usually provided to the engine's combustion chambers by a carburetor; ignition is achieved by exposing the mixture to an electrical spark. In recent years, exhaust treatment devices, the most important being the catalytic converter, have been added to these engines to reduce air pollution.

b. Stratified Charge Otto

Except for a non-uniform air-fuel mixture, the stratified charge engine is basically the same as the conventional Otto.

There are two major types of stratified charge engines. The first is a carbureted type, which achieves stratification of the charge through a division of the combustion chamber into two parts. One such divided chamber engine, the Compound Vortex Controlled Combustion engine (CVCC), was introduced on production cars by Honda in 1973.

The second type uses fuel injection to achieve stratification in an undivided or "open" combustion chamber. As of 1979, no such engine had appeared in cars sold to the public.

c. Diesel

The Diesel engine is also an internal combustion engine. However, the air-fuel charge is exploded by compression instead of electrical ignition. Diesel fuel is heavier and less refined than gasoline. An automotive diesel was first introduced in 1952 by Mercedes-Benz. At the end of 1977, G.M. began to sell the first diesel cars produced in the United States.

d. Rotary

The rotary or Wankel engine is a spark-ignited internal combustion engine. Unlike the Diesel and Otto, the rotary's moving member (the rotor) has a circular rather than reciprocating motion. There are uniform and stratified charge versions of the rotary engine. Since the 1960's, uniform-charge rotary engines have appeared on cars built by NSU and Toyo Kogyo.

e. Gas Turbine

The turbine is also an internal combustion engine. Unlike the Otto, Diesel, and rotary, however, combustion is not intermittent, but instead is continuous. Motion is created by directing a constant flow of hot gases against a pinwheel-like moving member. There are two basic types of gas turbine engines. The free turbine type uses two moving members and a conventional transmission; the single shaft type has only one moving member and requires a continuously variable transmission. Gas turbines have never been

offered on production automobiles. The turbine is sometimes called the Brayton engine.

f. Rankine

The Rankine engine is an external combustion engine. In this type, a working fluid is vaporized by an external heat source and, as a result, expands against the engine's moving member to produce power; the fluid is condensed to repeat the cycle. Steam engines are Rankine engines that use water as the working fluid. Steam engines enjoyed some popularity as an automotive powerplant around the turn of the century but had disappeared from the scene by the 1920's.

g. Stirling

The Stirling engine is also an external combustion engine; in it a small quantity of a gas is alternately expanded and contracted to produce power. In addition to using a non-condensable working fluid, the Stirling works on a different thermodynamic cycle than the Rankine. Like the gas turbine, the Stirling has never been used in production automobiles.

h. Electric Powerplants

Electric powerplants use electro-magnetic forces to produce motion. Energy is stored in a battery (in effect, the system's fuel tank) and is transferred to a motor that converts the electricity into kinetic energy. Electric vehicles were not uncommon in this country during

the early 1900's, but, like steam cars, were eventually displaced by Otto-powered cars. Today, on-the-road electric vehicles are used in fairly great numbers in the United Kingdom. In 1975 the electric vehicle population in the UK was "estimated to exceed 130,000 vehicles; 70,000 to 75,000 of these are industrial trucks . . . and the other 55,000 to 60,000 are registered road vehicles."¹

3. The Characteristics of a Powerplant

This section offers a framework for the comparison of alternative powerplants. A particular design configuration of a type of powerplant can be described by a n -dimensional vector of characteristics $(z_{x1}, z_{x2}, \dots, z_{xn})$, where z_{x1} is, for instance, the unit manufacturing cost of the configuration x , and z_{x2} is fuel efficiency, and so forth.

For a given powerplant, and at some fixed level of technology, there are apt to be many possible design configurations, each exhibiting a different vector of characteristics. The set of possible design configurations for a given powerplant may be collectively expressed by a function

$$(1) F(z_1, z_2, \dots, z_n) = 0.$$

The various characteristics are apt to be interdependent. Tradeoffs may exist between characteristics i and j , that is,

$$(2) \partial z_i / \partial z_j < 0.$$

Or, powerplant characteristics may vary directly with each other, that is,

$$(3) \partial z_i / \partial z_j > 0.$$

The most important characteristics of automotive powerplants are now considered.

a. Unit Cost of Manufacture

A major operation in the production of a car is the building of the powerplant. Consequently, its cost bulks large in the total cost of the product. The costs of powerplant manufacture can be broken down into fixed and variable components. Fixed costs include factory and machinery depreciation, amortization of special tools, property taxes, and administrative expenses. Variable costs include expenses for labor, components, and other semi-finished and raw materials. Along with the demand for the firm's cars, the levels of variable and fixed cost of powerplant manufacture determine the profit-maximizing rate of output and level of profitability at that rate.

Powerplants can differ in either variable or fixed costs. Variable costs are sensitive to differences in structural materials or labor requirements; fixed costs vary from powerplant to powerplant if there are differences in the capital intensities of their production.

If a powerplant has a lower unit cost than another, ceteris paribus, the former is superior. Substitution of the cheaper for the dearer would increase the profits of

the firm; if the innovation leads to a lower price for the car, consumer surplus would increase as well.

b. Driveability

Driveability is an industry term that refers to a car's performance in running. One aspect of driveability (and sometimes synonymous with it) is flexibility. This has to do with a powerplant's ability to accelerate the vehicle. In lay terms, a powerplant with great flexibility is "full of pep," while the response of a less flexible engine seems "sluggish." Ease of starting can also be included under the heading of driveability. Another item that can be included is smoothness; this refers to the level of vibration.

It is reasonable to assume that consumers prefer a powerplant with superior driveability, ceteris paribus. It is assumed that this preference is expressed by a willingness to pay a premium for such a powerplant.

c. Fuel Efficiency

The largest operating cost of an automobile is fuel. Although many things affect a car's fuel economy,² an important factor is the efficiency of the powerplant in converting the energy stored in fuel to motion.

It is reasonable to assume that consumers prefer powerplants with greater fuel efficiency, ceteris paribus. The preference for high fuel efficiency is apt to increase with the price of fuel. Moreover, the price of re-fueling is

not its monetary cost alone, but its time cost: recent experience with government allocation schemes suggests that the time costs of obtaining fuel are not always trivial.

d. Maintenance

Another operating cost is maintenance. The cost of maintenance should also be thought of as the sum of monetary and time costs. Aside from "buffs" who enjoy working on their cars, most consumers prefer less maintenance, ceteris paribus.

e. Durability

Durability is a virtue since long life tends to be translated into high economic value. Consumers, it is assumed, prefer more durable powerplants and signal this preference by a willingness to pay a premium for a long-lasting motor; even though the consumer may not keep his car until the powerplant is worn out, the premium can be recouped upon resale.

f. Weight of Powerplant

The weight of a powerplant affects the design of a car's other components and its fuel economy. The heavier the powerplant, the heavier the required support components in the chassis and suspension; this also increases the car's cost of production. Added weight also means higher fuel consumption. It can be concluded, therefore, that both producers and consumers prefer lighter powerplants, ceteris paribus.

g. Size of Powerplant

The size of a powerplant also affects the design of other automotive components. Given a set of external dimensions, the more room devoted to the powerplant, the less available for passengers and cargo. It is assumed, therefore, that small powerplants are superior, ceteris paribus.

h. Noise

Except for some individuals who need an audible display of conspicuous consumption, it is assumed that consumers prefer less noisy powerplants, ceteris paribus. Noise also generates negative externalities, but this social effect is not taken into account by presumably ego-centric buyers.

i. Control of Emissions

Federal law sets maximum allowable levels for three pollutants: hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen (NOx). The final levels of federal emission standards have yet to be settled. Rules on other kinds of pollutants may be established in the future.

Since automotive emissions are an externality, the individual consumer is indifferent to his own car's contribution to air pollution. Consequently, automakers have the incentive to select a powerplant configuration which just satisfies the law.

So much for the most important powerplant characteristics.

It is easy to see some of the tradeoffs (e.g., weight-fuel economy) or the complementarities (e.g., cost-durability) that exist. Other relationships, such as the tradeoff between control of emissions and fuel economy, are not as obvious to the lay mind.

The production of new technology changes the relationships between powerplant characteristics. More precisely, technological progress reduces the constraints which these relationships impose.

An enlightening example involves recent changes in the conventional Otto. Beginning in 1968, national automotive emission standards were established by the federal government. For the 1970 model year, the standards allowed maximum emissions of 4.1 grams per mile (gpm) of HC and 34 gpm of CO; in comparison, emissions from a typical uncontrolled auto were roughly 10.5 gpm of HC and 84 gpm of CO. Stricter standards for HC and CO were put into effect in 1972 and again in 1975. Moreover, beginning in 1973 federal standards were established for NO_x at a level of 3.1 gpm; this compares to a level of 4.1 gpm of NO_x for a typical uncontrolled car.³ As a result of the standards, automotive engineers had to reduce the level of engine emissions; these efforts had impacts on other powerplant characteristics.

Consider the period between 1968 and 1973. To meet the standards, the firms made changes in the carburetion, ignition and valve timing, compression ratios, and, to

control NOx, added exhaust gas recirculation. These changes increased cost around \$100 per car.⁴

Another powerplant characteristic affected by the reduction in allowable emissions was driveability. The Dupont Company estimated that "for representative full size cars produced from 1968 to 1973," changes to control emissions increased acceleration time (from 0 to 60 miles per hour) by 10 percent.⁵ For the same cars, moreover, Dupont estimated that the changes made for emissions increased fuel consumption about 17 percent.⁶

Eventually, however, technological progress eased the constraints faced by automotive engineers: the major breakthrough was the introduction of the catalytic converter at the end of 1974. Tighter federal emission standards were scheduled for 1975. Although they could have been met without the use of the catalytic converter, fuel economy would have dropped five percent relative to 1974 levels. Moreover, driveability would have worsened, perhaps to the point of jeopardizing car sales.

With the catalytic converter, however, the job of reducing the level of pollutants is accomplished by treating the exhaust gases after they have left the engine:

The addition of the catalytic control system in 1975 models resulted in reductions in tailpipe HC and CO levels but allowed 35% and 75% increases in the "raw" emissions of HC and CO respectively. The catalyst system gave manufacturers the flexibility to re-optimize the basic engine for fuel economy by shifting some of the emission control burden to an after-treatment device

The combined effect of using catalysts and lead-free fuel has resulted in a level of fuel economy for many cars which is equal to or higher than the fuel economy achieved by pre-1968 models which were not emission controlled.⁷

The use of the catalytic converter also improved driveability and reduced maintenance costs in comparison to 1974 levels.⁸ To be sure, these benefits did not come free: the catalytic converter added about \$100 to the sticker price of automobiles.⁹

The introduction of the catalytic converter is but one instance of how production of new technology changes the function of powerplant characteristics. Although it is convenient to consider a short run when the relations between powerplant characteristics are fixed, the function's evolution is continuous, the speed of which depends on the rate of technology production.

4. The Test for Type III Suboptimization

For a sufficiently short period, the level of technology is essentially fixed. Assume such was the case between and including 1973 and 1977; also assume the existence of stable functions, which describe the characteristics of the various powerplants.

During this period, American automakers (with the exception of G.M. at the end of 1977) continued to rely solely on the conventional Otto. Assume that of all the possible design configurations of the conventional Otto, the automakers selected that configuration, or range of

configurations, that maximized the sum of producer and consumer surpluses.

The conventional Otto, as revealed in practice during the mid-1970's, serves, therefore, as the benchmark to determine the worth of alternative powerplants. If it can be shown that some alternative is superior to the conventional Otto (in that it would increase the surpluses of either producers or consumers) in one characteristic, while at least equal to the conventional Otto in the remaining ones, Type III suboptimization is indicated. If, however, an alternative is superior to the Otto in some characteristics but inferior in others, the test for Type III suboptimization is ambiguous; a verdict may be suggested, however, by a preponderance of evidence.

5. Dominance of the Conventional Otto

Before comparing the various powerplants, it is worthwhile to discuss the present dominance of the conventional Otto; this requires a review of some early automotive history.

At the turn of the century, steam, electric and Otto powerplants were used in cars. For a few years, none of the three seemed destined for dominance. Each had a camp of dedicated followers which proclaimed the virtues of their favorite, and there was much confusion about which powerplant was best.

Yet, by 1905, the Otto was in ascendancy. By 1910, the market shares of steam and electric cars had become insignificant.

That steam and electric powerplants were able to hold their own against the Otto for a while was due to their superiority in some characteristics. Steam cars were superior in acceleration and speed; due to the high torque generated at low engine speeds, gear shifting in steam cars was not necessary. To be sure, there were offsetting factors in the driveability of early steam cars; they needed several minutes to warm up; frequent stops were needed to refill the engine's water supply, and in winter freezing was a problem.

The electric car also had advantages over the Otto. Starting was instantaneous and gear changing was no problem. The electric vehicle was more durable and required less maintenance than steam or Otto-powered cars, since the motor was not subject to the stresses of heat and pressure. But the time cost of re-fueling was high: the typical electric vehicle of 1900 could go no farther than twenty miles without a recharge that took from eight to twelve hours; a top speed of only twenty miles per hour was another drawback.¹⁰

In contrast to electric and steam cars, the driveability of early Otto cars was very poor. Early Ottos were not very powerful. As a result, drivers were forced to change gears frequently; with the unrefined transmissions of the day, it took considerable skill to shift smoothly. Furthermore, starting required that the crankshaft be put in motion by some external force. Before the introduction

of the electric starter in 1911, this meant muscle power. The operation of the handcrank was not only cumbersome but dangerous, since the crank had a tendency to kick back once the engine had started. Other liabilities of the early Otto were vibration, noise, and emissions of noxious fumes: steam and electric powerplants were easily superior to the Otto in these characteristics.

Why, then, did the industry adopt the Otto? One crucial factor was the Otto's low weight to power ratio. Less structural material in the powerplant was needed for a given output of power than in either electric or steam powerplants. A lighter engine also meant that supports in the rest of the car could be lighter. All of this meant lower production costs for Otto-powered cars.

It is noteworthy that the weight to power factor was largely responsible for the abandonment of steam in favor of the Otto by automobile pioneers such as R.E. Olds¹¹ and Comte de Dion.¹² Henry Ford also experimented with steam before turning to internal combustion; he later wrote of the steam carriage that he had built in 1879:

It had a kerosene-heated boiler and it developed plenty of power and a neat control--which is so easy with a steam throttle. But the boiler was dangerous. To get the requisite power without too big and too heavy a powerplant required that the engine work under high pressure; sitting on a high pressure boiler is not altogether pleasant. To make it even reasonably safe required an excess of weight that nullified the economy of high pressure. For two years I kept experimenting with various sorts of boilers--the engine and control problems were simple enough. I definitely abandoned the whole idea of running a road vehicle by steam.

. . . [this work] served to confirm the opinion I had formed that steam was not suitable for light vehicles.¹³

The Otto enjoyed an even greater cost advantage over electric powerplants. Since the cells of the electric vehicle's battery were poor reservoirs of energy, a large number were needed for acceptable acceleration and range. But a large number of cells made the battery bulky and expensive.

The differences in cost between the two powerplants was reflected in the prices of their respective vehicles. Electric vehicles never penetrated the lower price ranges where Otto-powered cars had success. For instance, the Columbia Electric car of 1900, which was produced at a volume of about 1500 units, sold for \$3000.¹⁴ In contrast, the Otto-powered curved-dash Oldsmobile of 1901, produced at a volume of around 425 units, sold for only \$650.¹⁵ Even during the peak years of electric vehicle sales, 1910-1915, prices remained high; although two models were offered for under \$2,000, the average electric vehicle carried a price of around \$2,800.¹⁶ By this time many Otto-powered cars were available for under \$1,000.

The second reason for the dominance of the Otto is that technological progress favored it. Progress eliminated or markedly reduced the major faults of the Otto: the introduction of more powerful versions of the engine reduced its disadvantage vis-à-vis steam in speed and acceleration and increased its advantage over electric powerplants in these respects; greater power, plus improvements in

transmissions made gear changing less difficult; and advances in lubrication, metallurgy, and vibration control increased the durability and smoothness of the Otto-powered automobile.

This is not to say no progress was made in steam and electric powerplants. Steam car producers were able to shorten warm-up time and to reduce water consumption. Electric vehicle producers were eventually able to offer cars with somewhat improved range and speed. However, whatever improvements were made in steam and electric powerplants, they were simply not enough to turn back the onslaught of the low-cost Otto.

It is important to point out that if a test for Type III suboptimization were to be conducted on the basis of, say, the level of technology in 1920, the result would be ambiguous. Even at that date, when all but a tiny fraction of cars were equipped with Ottos, there were some characteristics in which steam and electric powerplants were superior. Ultimately, therefore, a decision on Type III suboptimization in an ambiguous case must be based on response of a workably competitive market.

6. Sources of Technological Information

Two groups of sources are used to evaluate the state-of-the-art of powerplant technology during the mid 1970's. One group is made up of the Big Three's testimony before Congressional committees, their submissions of data to the

Environmental Protection Agency, and other corporate reports and publications.

The second group is made up of a number of important "outside" studies of the automotive powerplants. One study is a 1973 analysis by the Eaton Corporation, an important automotive supplier.¹⁷ A second is a 1975 report by the Jet Propulsion Laboratory, which is especially noteworthy for its exhaustive treatment of the powerplant question.¹⁸ The third study was done in 1976 by the Energy Laboratory of the Massachusetts Institute of Technology; this report covers only the diesel, electric, and Stirling powerplants.¹⁹ A final study in this group is another report of the Jet Propulsion Laboratory that was prepared for the Department of Energy in 1978.²⁰

While the sources are not always in agreement, and while it is sometimes difficult to compare their data, they give a good idea of the merits of the various powerplants and opportunities in this area of technology.

7. Stratified Charge Engine

a. General Motors

G.M.'s version of the carbureted stratified charge engine is called the Dilute Combustion Jet Ignition Engine. In 1975 the firm reported that the engine:

. . . has been under study at the G.M. Research Laboratories and throughout the world for many years as an approach to better fuel economy, and has more recently been recognized as being of some assistance in automotive emission control.²¹

In particular, emissions of CO and NOx were found to be low.

Moreover, G.M. stated that "in both cost and fuel economy, these engines appear now to offer promise of equalling the performance of our 1975 model conventional engines with catalytic converters."²²

By 1977 further work showed that at the lower levels of exhaust emissions that the firm had to meet by 1981, "fuel economy was unacceptably poor."²³ It seemed the engine's good fuel economy at low levels of emissions control disappears as the level of control is increased. To be sure, fuel economy could be improved by retuning the engine and letting the exhaust be treated by a catalytic device. This, however, would make the engine at least as costly as the conventional Otto. G.M. concluded that a "NOx standard of 2.0 gpm or more appears necessary to keep the stratified charge engine as a viable alternative across the full range of today's U.S. vehicle lines."²⁴

An additional problem with the engines, according to G.M., "has been their tendency toward unreliable initiation and unstable burning. These lead to driveability problems and the inability to operate over a wide range of operating conditions."²⁵ Another disadvantage is a "slight" loss of power relative to the conventional Otto.²⁶

Work on the fuel-injected, open chamber type of engine does not appear to have begun at G.M. until after 1975. For this reason, G.M.'s remarks are not very informative on this type of engine. According to the firm, high fuel economy

and low levels of CO and NOx emissions were the engine's main attraction.²⁷

b. Ford

Ford's test of a large divided chamber stratified charge engine indicated "the capability to combine low emissions of HC and CO with good fuel economy."²⁸ Ford found the driveability of the test cars to be satisfactory. However, Ford found control of NOx was "borderline" for 2.0 gpm standard and emissions levels were "very sensitive to the proper operation of all fuel and spark control devices."²⁹ Like G.M., Ford was concerned about the engine's ability to meet stricter standards for NOx without loss of fuel economy and without use of additional exhaust treatment devices. It was stated that the prechamber engines under investigation were relatively expensive and complex.³⁰

Ford's fuel-injected, open chamber stratified charge engine is called the Programmed Combustion (Proco) engine. This engine, according to Ford, "shows promise of significantly improving gas mileage while also controlling automotive pollution."³¹ Driveability of the Proco was cited as "good" even "with low emission type adjustments."³²

Ford warned, however, that "there continue to be uncertainties with respect to this engine's durability, reliability of complex controls, catalyst efficiency at lower exhaust temperatures, complex new pump design, and compatibility with other product changes."³³

c. Chrysler

Chrysler sources are not very helpful on the divided chamber configuration. In 1975 Chrysler's engineering vice president spoke about the engine before a Senate committee:

Senator, the prechamber engine, which is the Honda CVCC engine, is not new to the industry. It has been around for, I guess, 30 or 35 years. It first made its appearance in the industry to improve fuel economy. At that time it was competing with the old "L" head combustion chamber design, which was pretty inefficient. And nobody could produce as good fuel economy with the prechamber as they could with the "L" head.

Since then the industry has gone to overhead valves, much higher efficiency engines, and the prechamber still has a fuel economy problem

Again, the engine they have in the Civic gets a fuel economy that is somewhat less than one of the other Japanese engines where the car weighs 400 or 500 pounds more and the heavier car is getting better fuel economy than the Honda.³⁴

Chrysler was more optimistic about the open chamber type of stratified charge engine. The particular configuration that Chrysler was experimenting with during the mid-1970's was originally developed by Texaco; it has been referred to as the Texaco Controlled Combustion System (TCCS). Chrysler predicted:

. . . that widespread use of engines of this type could provide up to 35 percent more vehicle miles for the same amount of crude oil processed by the refineries. This results largely from the improved engine efficiency, and from the multi-fuel capability of the engine which permits significantly greater yield from each barrel of crude oil.³⁵

Moreover, emissions levels appeared "attractive."

On the other hand, "current cost forecasts indicate somewhat higher penalties for the TCCS than for a conventional engine modified for comparable emissions." Chrysler went on to add that "other factors such as driveability, noise, and durability, also require further development."³⁶

d. Eaton

Unfortunately, the Eaton study did not separately evaluate the divided chamber and open chamber types. For the group as a whole, Eaton found that stratified charge engines have "shown potential for low emissions," and that a "slight" advantage in fuel economy over the conventional Otto was likely.³⁷ It also noted that noise, smoothness, and durability should be similar to conventional engines.

Whether the stratified charge engine had an advantage in manufacturing cost depended on the required level of emissions control. In comparison to conventional engines without catalysts, some increase in cost was found likely. However, it was possible that stratified charge engines could be cheaper than conventional engines if the latter were used with a sophisticated catalytic system; Eaton did not indicate the level of emissions control at which the cost advantage swung to the stratified charge.

Similarly, Eaton concluded that "stratified charge engines should require slightly more maintenance than uncontrolled engines," but "somewhat less maintenance than engines with dual catalysts."³⁸ Finally, stratified charge

engines were considered to be probably at some disadvantage in driveability, weight, and size.

e. JPL-1975

The main object of this study was the identification of the powerplants whose future evolution appeared likely to produce an alternative superior to an also evolving conventional Otto.

A powerplant's state of development was divided into three periods: present, mature, and advanced. The present configuration was the powerplant as it existed in 1975, manifested in either prototype or production versions. The mature configuration was defined as a near-term improved version of the present configuration "as limited by current technology."³⁹ Finally, the advanced configuration was "defined as a longer-term future version of an engine which embodies advantages afforded by extensions of existing technology"; such configurations, the JPL assumed, would probably not be ready for production before 1990.⁴⁰

It is the set of mature configurations which is of interest with respect to Type III suboptimization. That is, given the state of technology in the mid-1970's and the probable marginal advances which can be foreseen, could a firm have justified action which would have as its eventual result the replacement of the conventional Otto?

The comparison, or "baseline" engine, was the mature version of the conventional Otto. With the exception of electronic carburetion and the use of a three-way catalytic

system, the mature version of the conventional Otto was assumed to be essentially identical to the engines in 1975 model year cars. The mature version of the conventional Otto was assumed capable of meeting federal emission standards of 0.41 gpm HC, 3.4 gpm CO, and 0.4 gpm of NOx.

Not only were the mature versions of the various alternative powerplants assumed to meet these standards, but it was further assumed that they had "Otto-equivalent" driveability, safety, durability, noise, accessories (power steering, air conditioning, etc.), range, and passenger and cargo accommodations. Thus the comparison of the powerplants comes down to differences in manufacturing and operating costs.

The divided chamber type of stratified charge engine was not projected in evolution to either a mature or advanced configuration. According to the JPL, "of the various SC Otto implementations, the direct-injected . . . open chamber type was found to offer the greatest potential in vehicle fuel economy with simultaneously low HC and NOx. . . ." ⁴¹ As a result, the open chamber configuration was selected for evaluation.

The unit manufacturing cost of the mature stratified charge engine was estimated to be around 34 dollars greater than that of a mature conventional Otto of equal power. Fuel economy was projected to be about 12 percent better in the city and 3 percent in highway driving; maintenance cost for the stratified charge and the conventional Otto appeared to be about the same.

Based on these estimates, it was concluded that the incremental cost of ownership⁴² tended to show some advantage for the stratified charge engine (see Table One). But according to the JPL, "the differentials for the SC Otto are very small, however, and within the uncertainty of the calculations probably represent parity."⁴³ Furthermore, JPL's calculations on ownership cost are sensitive to the assumed prices of fuel, the discount rate, and profit margins for the manufacturers and dealers.

f. JPL-1978

The concept of an Otto-engine equivalent (OEE) is used in this study also. Fuel economy estimates for full-sized and small OEE vehicles were made; these estimates were made under the assumption of emission standards of 0.4 gpm HC, 3.4 gpm CO, and 1.0 gpm NOx. Comparisons between the various engines were made for both 1978 production vehicles (where applicable) and for projection for 1985.

For 1978 production vehicles, JPL estimated virtually no difference in fuel economy with respect to a full-sized car; an average fuel economy of 18 mpg was estimated for both the stratified charge and the conventional Otto. Since the Honda CVCC was the only stratified charge engine in production as of 1978, the comparison necessarily involved the divided chamber type. For the small car, the stratified charge engine was estimated to have poorer fuel economy than a comparable conventional engine; it was estimated that the average fuel economy for the stratified charge engine was

TABLE 5
Ownership Cost Differential^a for Mature Otto-Engine-Equivalent Cars
(Increment above baseline vehicle; per vehicle, in 1974 dollars)

Engine Type	Vehicle Class					
	Small		Compact		Full-Size	
	35,000 miles, ^c 3 years	Life-cycle 100,000 miles in about 10 years	35,000 miles, ^c 3 years	Life-cycle 100,000 miles in about 10 years	35,000 miles, ^c 3 years	Life-cycle 100,000 miles in about 10 years
Baseline UC Otto	0	0	0	0	0	0
UC Otto (oxidation catalyst only) ^b	-50	-150	-100	-200	-100	-200
SC Otto	-50	-50	0	-50	50	0
Diesel						
Brayton (single shaft)	-50	-300	-250	-600	-350	-850
Brayton (free turbine)	-50	-150	-100	-300	-150	-450
Stirling	100	-250	-150	-450	-200	-600
Rankine	150	350	250	400	350	550

^aPresent value at 7% annual discount rate; 52¢/gal gasoline, 49¢/gal diesel fuel, and 48¢/gal broduct fuel. All incremental costs rounded to the nearest \$50. Purchase price assumed to be equal to the sum of unit manufacturing cost, corporate overhead, a markup to generate a 15% rate of return on investment, all times at 1.3 dealer mark-up factor.

^bMature UC Otto engine meeting 2.0 g/mi NOx standard rather than 0.4 g/mi NOx.

^cThis approximates the ownership cost to the first owner and is based on an assumed constant resale percentage (for each car class). In actuality, the high-fuel-economy, low-maintenance car would be expected to have higher resale value and look even more attractive.

Source: Jet Propulsion Laboratory, Should We Have a New Engine?, 1975, Vol. 2, p. 20-12.

approximately 32 mpg compared to 34 mpg for a small car powered by a conventional Otto.

In the projections to 1985, the fuel injected, open chamber type of stratified charge engine was assumed. JPL concluded that the stratified charge engine would have poorer fuel economy for both the small and large vehicle compared to the conventional Otto of 1985 (see Tables 6 and 7). Unfortunately, this study provided no estimates of manufacturing or ownership costs.

8. Diesel

a. General Motors

In 1974 a G.M. spokesman stated "that a passenger car with a diesel engine would provide a fuel savings of about 25%" in city driving compared to a vehicle with a conventional Otto.⁴⁴

The power to weight ratio for the Diesel was inferior to the conventional Otto and, as a result, acceleration was poorer. (The Diesel's greater weight is primarily due to the more rugged construction of the engine block, which is necessary to withstand the high pressure created by compression ignition.)

Moreover, according to G.M., the Diesel had other disadvantages:

However, the diesel engine traditionally has had certain other characteristics which make it less desirable for passenger car use from the viewpoint of both customer acceptance and protection of the environment. Increased engine weight, higher cost, and the difficulty of starting in cold weather detract from customer

TABLE 6
Fuel Economy Projections for 1985 Full-Size Cars Using Various Engines

Power System	Transmission (1)	MPG-City		MPG-Highway		MPG-Composite	
		Diesel	Gasoline Equivalent	Diesel	Gasoline Equivalent	Diesel	Gasoline Equivalent
Conventional Engines							
UC Otto	M4		15.1		23.8		18.1
	M5		16.6		30.0		20.8
NA Diesel (2)	M4	22.8	20.1	25.5	22.5	23.9	21.1
	M5	24.9	22.0	31.7	28.0	27.6	24.3
TC Diesel (3)	M4	20.7	18.3	31.4	27.7	24.5	21.6
	M5	21.9	19.4	35.8	31.5	26.6	23.4
Rotary UC Otto	M4		16.9		26.6		20.2
	M5		17.6		29.6		21.5
SC Otto	M4		14.7		23.6		17.7
	M5		15.5		27.7		19.3
FT Brayton (metal)	M4	23.0	20.3	45.9	40.5	29.7	26.2
	M5	21.0	18.5	44.1	39.0	27.5	24.3
SS Brayton (metal)	CVT	22.5	19.8	42.1	37.2	28.5	25.1
Stirling (metal)	M4		22.6		38.7		27.8
	M5		22.8		42.7		28.8

(1) M4--four-speed manual; M5--five-speed manual; CVT--continuously variable transmission.

(2) Naturally aspirated.

(3) Turbo-charged.

Source: Jet Propulsion Laboratory, "Automotive Technology Status and Projections," 1978, Vol. 2, pp. 9-39, 9-40.

TABLE 7
Fuel Economy Projections for 1985 Small Cars Using Various Engines

Power System	Transmission (1)	MPG-City		MPG-Highway		MPG Composite	
		Diesel	Gasoline Equivalent	Diesel	Gasoline Equivalent	Diesel	Gasoline Equivalent
Conventional Engines							
IC Otto	M4		29.5			41.1	33.8
	M5		31.4			46.3	36.7
NA Diesel (2)	M4	40.3	35.6	46.1	40.6	42.7	37.7
	M5	43.2	38.1	53.4	47.1	47.2	41.7
TC Diesel (3)	M4	37.7	33.3	53.0	46.7	43.2	38.2
	M5	39.2	34.6	56.8	50.1	45.5	40.2
Rotary IC Otto	M4		31.7		44.1	36.3	36.3
	M5		32.6		47.2	37.9	37.9
SC Otto	M4		27.5		39.8	31.9	31.9
	M5		28.7		44.8	34.2	34.2
FT Brayton (metal)	M4						
	M5	36.8	32.5	56.1	49.5	43.6	38.4
SS Brayton (metal)	CVT	35.3	31.1	52.6	46.4	41.4	36.6
Stirling (metal)	M4		41.7				46.3
	M5		42.2				48.7

(1) M4--four-speed manual; M5--five-speed manual; CVT--continuously variable transmission.

(2) Naturally aspirated.

(3) Turbo-charged.

Source: Jet Propulsion Laboratory, "Automotive Technology Status and Projections," 1978, Vol. 2, pp. 9-44, 9-45.

approval. Lack of customer acceptance is shown by the fact that even in Europe, where the diesel has been offered virtually since World War II and where the fuel economy incentive has been much stronger in the past than in the United States, last year only 3%, approximately, of the passenger car market was diesel powered.

In addition, noise, smoke, odor and particulate emissions still represent disadvantages which pose serious environmental problems if a substantial portion of our passenger car fleet were to be converted to diesel engines.⁴⁵

The Diesel was found capable of meeting the strictest standards now envisioned for HC and CO emissions. On the other hand, G.M. stated that "it is unable to attain the 0.4 gpm nitrogen oxide standard."⁴⁶

The Clean Air Act amendments of 1977 had a provision which waived the 1981 NOx standard for diesel-powered cars. This, plus a successful development program which reduced some of the Diesel's drawbacks, encouraged G.M. to introduce the engine on some of its American-built cars in late 1977.⁴⁷

b. Ford

In a 1975 submission of data to the EPA, Ford cited the results of a recent study of the Diesel by the British engineering firm, Ricardo and Company Engineers (1927) Ltd.,⁴⁸ prepared under contract to the EPA. According to Ford, the Ricardo study concluded that:

. . . the technology exists to build a diesel engine that would perform as well as a 130 hp gasoline engine in a 3500 lb. sedan, although such a diesel does not now exist. The diesel would offer up to 50% greater fuel economy, improvements in durability and reliability, and it should be able to meet 1977 emission standards (.41 gm/mi HC, 3.4 gm/mi CO and 2.0 gm/mi NOx). However, it would be worse than the gasoline

engine in terms of size, weight, cost, and cold-start characteristics, and odor, noise, particulate emissions and smoke would be slightly worse under normal driving conditions. In addition no diesel can presently meet the 0.4 gm/mi NOx standard without significant deterioration.⁴⁹

Ford believed Ricardo's estimate of the Diesel's fuel economy advantage was somewhat overstated.

Moreover, on the basis of its own tests, Ford stated that "substantially improved starting characteristics would be required before a diesel would be acceptable to the general public," and that "the smoke exhausted during winter time cold start is objectionable and would pose problems under conditions of simultaneous winter time starting in high vehicle density parking lots."⁵⁰

c. Chrysler

In its request for suspension of the 1977 emission standards, Chrysler reported the results of recent tests of Diesel engines:

It was concluded that a prototype installation was feasible for development purposes but that considerable engine and vehicle modification would be required for an acceptable production package. Vehicle fuel economy, performance and emissions predictions were made from the engine test data. It was concluded that there would be a 20-30% gain in fuel consumption (sic) over conventional engines at comparable performance levels at 1.5 to 2.0 grams per mile NOx. Hydrocarbon levels were undetermined, while CO was acceptable

. . . If emission limits were to be maintained at current 1976 levels, the continuing pressure for reduced fuel consumption would spur additional efforts to overcome the remaining obstacles to more widespread use of the automotive Diesel, i.e., noise, odor, bulk, and cost. However, the imposition of NOx and HC limits as required for 1978 discourages such efforts, since a great deal of combustion research is anticipated before we can assess the potential of the Diesel for meeting such requirements.⁵¹

d. Eaton

Eaton found that the Diesel had "a substantial fuel consumption advantage especially at light loads characteristic of passenger cars."⁵² The Diesel also received high marks for durability and low maintenance.

On the other hand, the Diesel was found inferior to the conventional Otto in flexibility, smoothness, noise, weight, and size. Also it was found to be "substantially more costly" to produce.⁵³

While Eaton concluded that the Diesel had "very low hydrocarbon and carbon monoxide emissions,"⁵⁴ these levels were probably not good enough to meet the proposed final standards of 0.41 gpm HC, 3.4 gpm CO, and 0.4 gpm NOx. Smoke and odor from the Diesel were cited as being objectionable.

e. JPL-1975

The Diesel, according to JPL, was found not to have a large fuel economy advantage over the conventional Otto. The fuel economy of the mature Diesel was estimated to be 19% better in the city than that of a mature Otto while only 5% better on the highway. Remember that in JPL's methodology for evaluating the alternative powerplants, it was assumed that all are equivalent in driveability, durability, etc.:

When evaluated on an equivalent vehicle basis, the widely acclaimed fuel economy advantage of the Diesel is considerably reduced To be weight- and performance-competitive with Otto powerplants, the Diesel required the additional complexity of turbo-

charging. While the Diesel can probably meet the emissions standards required for most of the country, as viewed today, it has no margin for further control if necessary.⁵⁵

JPL was particularly concerned with the Diesel's emissions of smoke (particulates) and odor:

Naturally aspirated (NA) Diesel emissions are seen to be virtually an order of magnitude greater than those of intermittent-combustion gasoline engines. The environmental significance in a conjectured all-Diesel fleet needs further study

. . . The exhaust odor question must be resolved in a fleet conversion to any combustion engine having such a potential problem. In the case of the Diesel, however, the problem does not appear to be yielding rapidly to technology, probably because it is fundamental to the combustion process.⁵⁶

Furthermore, JPL estimated that a 150 hp mature Diesel could be produced at \$781 per unit; unit manufacturing cost for a comparable conventional Otto was estimated to be \$121 less. As Table 5 indicates, JPL estimated a savings of around \$150 in lifetime ownership costs for the Diesel in comparison to the conventional Otto.

f. MIT

The MIT study contains an enlightening discussion of the tradeoffs between acceleration, fuel economy, and initial cost of the Diesel relative to the conventional Otto:

The diesel engine has lower specific power than the ICE [the conventional Otto], i.e., a lower power per unit displacement. The engine weight for equal displacement is higher than the ICE due to heavier construction and heavier duty auxiliaries. Thus, if engine displacement is held roughly equal to an ICE, the diesel vehicle is slightly heavier, and has significantly poorer performance. For equal vehicle performance to an equivalent size ICE vehicle, the diesel engine displacement must

be larger and the diesel vehicle is substantially heavier. Across this performance spectrum, there is a fuel economy advantage for the diesel, but the advantage decreases significantly as the diesel vehicle's performance approaches that of an equivalent-size ICE vehicle.⁵⁷

The relation between relative initial cost and relative acceleration, however, is a positive one:

At equal engine displacement (and 60 percent relative acceleration) the diesel engine initial cost would be between 1.1 and 1.5 times the ICE cost. At equal vehicle performance, the diesel engine initial cost would be 1.6 to 2.1 times the ICE cost.⁵⁸

As a result, the Diesel's operating cost (the discounted lifetime sum) relative to the conventional Otto is sensitive to the engine's design configuration:

At the equal engine displacement end of the relative diesel acceleration scale, the minimum estimated fuel economy gain relative to the average ICE vehicle (of the same weight) is 30 percent. At equal fuel and maintenance costs this improvement in efficiency would offset an initial engine cost relative to the ICE of about 1.5. The expected range of engine initial costs is 1.1 to 1.5. If a diesel fuel price advantage and a diesel maintenance cost advantage are assumed in addition, a net benefit seems assured. At the other end of the performance scale, equal vehicle acceleration, the fuel economy advantage of the diesel may be as little as 4 percent (though it may be as high as 30 percent); the initial engine cost ratio, diesel to ICE, is between 1.6 and 2.1. Also, the costs of body modifications are greatest at this end of the relative acceleration range. Thus under these conditions, the diesel is much less likely to show a total operating cost advantage, and certainly such an advantage cannot now be assumed.⁵⁹

As this passage implies, the study found significant savings in maintenance for the Diesel on the magnitude of several hundred dollars over the life of the engine.⁶⁰

In the area of emissions, the MIT study concluded that the Diesel could meet the strictest standards that have

been proposed for HC and CO. However, the proposed statutory standard for NOx (0.4 gpm) appeared unattainable; due to the nature of the combustion process of the Diesel, the control of NOx with catalysts was impossible. A level of 1.5 gpm of NOx was stated as the possible lower limit for full-size Diesel cars.

The emissions of odor and particulates by Diesel engines were called "potential emissions problems."⁶¹ Finally, the Diesel was found to be inferior to the conventional Otto in noise and smoothness.⁶²

g. JPL-1978

Under 1978 technology, fuel economy of the Diesel was estimated to be approximately fifteen to twenty percent greater than that of a comparable Otto, assuming a full-sized car; on small cars, a ten to twelve percent advantage was estimated.⁶³

Extrapolating to 1985, JPL estimated the variable production cost of a turbo-charged Diesel, expressed in 1977 dollars, to be around \$606 per engine compared to \$500 for a conventional Otto.⁶⁴ No estimate of the relative ownership costs was offered.

The Diesel's inability to meet NOx standards below 1.0 gpm was confirmed. Particulates and odor were also pointed to as problems.⁶⁵

9. Rotary Engine

a. General Motors

During the early 1970's, G.M. was engaged in an extensive program to develop the rotary. Indeed, G.M. said in late 1970 that it would try to offer the rotary on some production vehicles by the 1974 model year. "The principal advantage of the new engine concept," according to G.M. in 1973, "is its small size for a given output--50% smaller and 30% lighter. This opens up new avenues of vehicle configuration which can have significant indirect effects on vehicle size, energy and resource conservation, safety, and comfort and convenience."⁶⁶

However, in the fall of 1974, the introduction of the rotary was postponed indefinitely; this decision was based on the rotary's difficulties with federal emission standards; the control of HC was singled out as being especially troublesome.⁶⁷ Moreover, the rotary could not meet the standards "at reasonable fuel economy levels at reasonable cost."⁶⁸

b. Ford

While emissions of NOx tended to be lower, Ford found the rotary to emit more CO and HC than the conventional engine.⁶⁹

Moreover, Ford stated:

. . . the rotary engine was not able to achieve fuel economy comparable to a conventional engine. Because the inherently poor theoretical thermal efficiency which resulted in lower fuel economy than comparable

internal combustion engines, and because of the high unit and piece cost of the engine which were projected to be substantially higher than a conventional engine, Ford discontinued work on the rotary engine in January, 1974.⁷⁰

c. Chrysler

Chrysler's evaluation of the rotary was also unfavorable. Tests of the Mazda (Toyo Kogyo) rotary engine showed excessively high HC emissions and poor fuel economy. One Mazda car, selected for a 50,000 mile endurance run at Chrysler's test track, displayed a "fuel economy in the 10 to 11 miles per gallon range, a very poor level for a car of this size and weight."⁷¹ The problems of high HC emissions and low fuel economy led Chrysler to rule out the rotary as a competitive powerplant.

d. Eaton

Weight and size were cited by Eaton as the main advantages of the rotary engine:

Comparison of the lightest experimental Wankel with the lightest production piston engines indicates a 12-16% weight savings on a pound per horsepower basis Comparing the lightest and most compact engines shows size advantages in the range of 35-45% based on a "box" volume (max. length x max. height x max. width).⁷²

The rotary and the conventional Otto were found roughly equal in noise and maintenance, while in smoothness the rotary was found equal or better than the conventional Otto.

On the negative side, the rotary was called a "rather dirty engine with emissions of hydrocarbons as much as five times higher, carbon monoxide up to three times higher,

while oxides of nitrogen are 75% less."⁷³ Expected improvements in the rotor seals would cut HC but, unfortunately, would raise NOx emissions.

Although lighter and with fewer parts than the conventional engine, the rotary, according to Eaton, "costs more than a piston engine."⁷⁴ Eaton pointed out that an engine's cost is a function not only of weight and number of parts, but its "technological density." Technological density includes materials, quantity and quality of machined surfaces, tolerances, surface treatments, and design complexity.⁷⁵

In short, the rotary is difficult to build:

In contrast to the piston rings, which are self-retained in place, Wankel seals are held in place only by gravity or friction with the seal springs trying to eject them. This suggests some difficult assembly problems not readily lending themselves to economical automation . . .

One of the areas of high cost is materials for and machining of the trochoid surface. While a great many material and treatment combinations have been tried, the most successful have been aluminum housings with either chrome by the Doehler-Jarvis transplant process, Elnisil (or tungsten carbide). Toyo Kogyo and NSU are believed to be using equipment capable of grinding four to five housings per hour (2 to 2½ engines/hr.). Recent reports indicate this may have doubled using diamond grinding wheels. Several U.S. machine tool builders have recently introduced prototype grinders capable of finishing 20-25 housings per hour (10-12 engines/hr.).

Typically, piston engines are produced at 100 or more/hr. It seems likely that another generation of machine tools will be required before high volume production would be economically practical.⁷⁶

Eaton also noted that since the introduction of the rotary by Toyo Kogyo in 1967, that firm's profits declined despite a doubling of its sales and a \$250 premium for its

rotary-equipped cars. During the last part of the 1970's, Toyo Kogyo replaced the rotary with a small conventional Otto on most of its cars; a more advanced rotary, however, was offered on a new, higher priced sports car. All of this suggests significantly higher manufacturing costs for the rotary.

Eaton also concluded that the rotary has substantially higher fuel consumption than the conventional Otto although the difference becomes smaller at higher levels of emissions control.⁷⁷ Finally, the rotary's flexibility and durability were considered somewhat inferior to the conventional Otto.⁷⁸

e. JPL-1975

The JPL classifies the rotary as a configuration of the uniform-charge Otto:

Presently-produced Wankel configurations are more inefficient, with higher HC and CO emissions . . . than their reciprocating counterparts. This is, in measure, attributable to the difficult geometric problem posed by the rotor seals and the tendency of the housing to thermally distort. There have also been claims that heat losses are greater than from equal-horsepower reciprocating configuration, by virtue of the higher surface-to-volume ratio in the Wankel's expansion space. However, it is not clear that these are really "fundamental" problems.⁷⁹

The report gives no additional details about the characteristics of contemporary rotary engines.

f. JPL-1978

The superior power to weight ratio of the rotary is reaffirmed in this report. As a result, the rotary "has

definite weight and packaging advantages over other conventional engines."⁸⁰

Significant improvements in the fuel economy of production rotary engines were reported. However, these improvements were not enough to eliminate the gap between the fuel economies of the rotary and those of production versions of the conventional Otto.⁸¹ Similar improvements in emissions control were also reported. However, no estimates of manufacturing cost were offered.

10. Rankine

a. General Motors

In Congressional testimony in 1974, G.M. presented its conclusions on the Rankine engine:

While emissions were reasonably low, one of the principal Rankine cycle problems is fuel economy. For example, reports of a recent California bus experiment indicated from three to five times more fuel usage than a corresponding diesel-powered bus. Our own SE-101 steam-powered car designed to meet all the performance and comfort of contemporary American passenger cars gave only 3 to 4 miles per gallon in city driving.

Other problems of the Rankine cycle include high weight and large size (particularly the heat exchangers for vaporizing and condensing), complexity in the mechanism and controls, cost, water consumption, water freezing and lubrication.

Although G.M.'s steam cars demonstrated in 1970 did not meet even the current 1976 emission standards, it did appear to us that lower levels might be attained with sufficient development work. In this respect, we have taken note of somewhat better emissions and fuel economy obtained in later experiments, using smaller vehicles, apparently with different performance and comfort criteria.⁸²

b. Ford

The most important advantage of the Rankine, according to Ford, is extremely low emissions.⁸³ Indeed, in bench test of Rankine engines, Ford was able to obtain emissions levels as low as 0.13 gpm HC, 0.19 gpm CO, and 0.26 gpm NOx.⁸⁴

Moreover, during Ford's experimental work with the Rankine, done in cooperation with the Thermo Electron Corporation, a non-toxic, non-flammable working fluid was developed that eliminated the freezing problem.

"Unfortunately," Ford stated, "the Rankine cycle engine has not been able to demonstrate attractive fuel economy, weight or size characteristics compared to conventional gasoline engines."⁸⁵

Ford's partner in the Rankine program, Thermo Electron, stated similar reservations about the engine:

It is now known that the organic Rankine cycle engine should be considered as a possible alternative power-plant in the long range, that is, on a greater than ten year time scale. This engine has demonstrated emissions levels well below the 1977 standards; but because the engine only has a fuel economy comparable with present internal combustion engines, improvements must be made in this area to offset the higher base cost of manufacturing the engine.⁸⁶

c. Chrysler

After completing an evaluation of the Rankine engine, Chrysler concluded "that to achieve emissions levels required for volume production, a host of technological and cost problems would have to be solved."⁸⁷ Chrysler went on to say:

Since the completion of this study, there has been considerable activity in the field, much of it resulting from governmental funded contracts (EPA, DOT, State of California). Good progress has been made towards demonstrating the 1976 emissions levels. However, considerable progress must still be made before a prototype powerplant could be built which would demonstrate adequate levels of fuel consumption, cost, and durability, in addition to a practical solution to the fluid/freezing problem.⁸⁸

d. Eaton

The Rankine was not evaluated by Eaton. The firm's manager of technological planning explained that "we did not consider steam engines as a serious contender based on previous studies indicating several shortcomings, notably, high fuel consumption."⁸⁹

e. JPL-1975

Although the JPL study discusses the technical specifications of a number of Rankine prototypes built during recent years, no detailed comparison with contemporary conventional Ottos is offered. However, data are presented on the fuel economies of three Rankine-powered cars that were built during the late sixties and early seventies by several inventor-firms. As Table 4 indicates, the fuel economies of these prototypes were greatly inferior to those of production cars.

The study projects a mature version of the Rankine; again, "a mature configuration is a near-term improved version as limited by today's technology."⁹⁰ Again, the Otto-equivalent concept was assumed.

TABLE 8

Fuel Economy of Rankine Prototypes and Selected Otto Production Cars

Rankine Prototype	Vehicle Inertia Weight, lb.	Miles Per ¹ Gallon, City	Miles Per ¹ Gallon, Highway
Carter Enterprises	2750	14.6	17.3
Steam Power Systems Corp.	3000	8.5	--
Aerojet-Liquid Rocket Co.	3000	5.8	--
Selected Otto Production Cars			
1973 Mercury Capri (Ford)	2750	17.5	--
1974 Chevrolet Vega (GM)	2750	18.9	--
1975 Chevrolet Vega (GM)	3000	21	29

Sources: Jet Propulsion Laboratory, Should We Have a New Engine?, 1975, Vol. 2, p. 7-20;
idem., "Automotive Technology Status and Projections," 1978, Vol. 2, p. 2-12.

Unit manufacturing cost for the mature Rankine was estimated to be much higher than that of the mature conventional Otto; a figure of \$965 (1974 dollars) was projected for the Rankine compared to \$660 for the conventional Otto.⁹¹

As for life-time ownership costs, the JPL concluded that "Rankine-engined cars do not 'pay back' in fuel savings their initial price differential, even at equal maintenance cost, and the situation worsens with increasing fuel price."⁹² As Table 5 indicates, the increment of the discounted life-time ownership cost for the Rankine over the conventional Otto was estimated to be between \$350 (small car) to \$550 (full size).⁹³

Very low emissions were cited by the JPL as the major bright spot for the Rankine.

f. JPL-1978

The Rankine engine was not evaluated in the second JPL study, presumably due to its unattractive fuel economy.

11. Electric Vehicles

a. General Motors

G.M. reported that as of 1975 its experiences with electric cars "were frustrating and disappointing." According to G.M., "existing batteries, including the most energetic batteries commercially available, couldn't begin to do an effective job in moving people in comparison with gasoline."⁹⁴

The low energy density of batteries, plus the inability to recharge batteries in a reasonably short time, were identified as the major obstacles which blocked commercialization:

To place it in proper perspective, for the same work done at the wheels as by 20 gallons of gasoline (58 kilograms) in an internal combustion engine, one would require about 5,000 kilograms of lead acid batteries or 600-700 kilograms of the best projected batteries. It becomes obvious why electric vehicles will continue to be much heavier than their internal combustion engine counterparts designed for the same mission.

Because of this battery limitation, electric vehicles are unable to match the performance and range of gasoline powered vehicles. They suffer from greater weight, both the battery weight and necessary added vehicle structure, and this weight penalty demands more propulsion energy. In addition, the original cost is high, and when amortization is considered, the operating cost also is high.⁹⁵

G.M. explained that a three-way tradeoff exists between acceleration, range, and battery life. As of the mid-1970's it appeared impossible to design an electric car good enough to make it competitive with Otto-powered cars.

Electric vehicles themselves do not produce fumes. The powerplants which supply the vehicles' energy needs do emit NOx and sulfur oxides, however. As a result, "the electric car would result in from 2.3 to 12 times as much pollution in the air from powerplants as from the exhaust of the gasoline-powered car."⁹⁶

G.M. compared the energy consumption of electric and conventionally powered cars. Three electric vehicles, a two-passenger "shopper," a two-passenger "commuter," and a four-passenger sedan were built. Some of the characteristics of these vehicles are presented in Table 9; data on a

TABLE 9

Comparison of Characteristics
of Three Lead Acid Electric Cars and an
Otto Powered Chevrolet Vega

Criteria	Shopper	Commuter	Sedan	Vega
Maximum car speed, km/h				
25% grade, 24 km/h headwind	--	72	72	--
0% grade, 0 km/h headwind	72	>97	>97	>125
Distance in 4 seconds, m	15	--	--	23
Distance in 10 seconds, m	--	91	91	122
0-48 km/h time, sec	20	--	--	6
0-72 km/h time, sec	--	30	30	12
5% grade speed, km/h	24	24	24	--
20% grade speed, km/h	>0	>0	>0	--
Electric vehicle range, km	40	80	120	--

Source: General Motors Corporation, "Energy Utilization Comparison of Gasoline and Battery-Electric Powered Urban Vehicle," GMR - 1978, November 1974, p. 3.

conventionally powered Chevrolet Vega are shown for comparison. Note the poor acceleration and limited ranges of the electric vehicles.

It was concluded that the energy consumption of electric vehicles (with lead acid batteries) relative to that of "gasoline powered cars with the same cargo capacity and performance" depended, in part, on whether the electricity and gasoline were derived from coal or crude oil. If crude oil were the original energy source, conventional cars would consume less energy per mile in all three size categories. If coal were the original energy source, electric vehicles appeared superior only in the smallest size class. The difference in energy consumption between petroleum and coal sources was attributed to the differences in efficiencies in generating electricity from oil and synthesizing petroleum from coal. The comparison was repeated with the more advanced nickel-zinc battery. Here the electric vehicles did better, especially if coal served as the original source of energy (see Table 10).

In short, for only the smallest vehicle did electric power show an unambiguous advantage in energy consumption over Otto-powered cars: "Increases in desired range, performance, or vehicle size beyond that of the shopper increase the electric vehicle energy consumption with respect to the gasoline powered version."⁹⁸

As further evidence G.M. referred to a study by the General Research Corporation.⁹⁹ In addition to evaluating

TABLE 10

Energy Consumption Ratios:
Electric Cars Relative to Otto-Powered Car

Lead-Acid Battery		
	<u>Petroleum</u>	<u>Coal</u>
Shopper	1.88 - 1.42	.97 - .73
Commuter	2.44 - 1.72	1.26 - .89
Sedan	3.41 - 2.22	1.76 - 1.14
Nickel-Zinc Battery		
Shopper	1.65 - 1.28	.85 - .66
Commuter	1.79 - 1.36	.92 - .70
Sedan	2.00 - 1.48	1.03 - .76

Source: General Motors Corporation, "Energy Utilization Comparison of Gasoline and Battery-Electric Powered Urban Vehicles," GMR-1978, November 1974, p. 7.

the performance of cars powered by improved versions of currently available lead-acid batteries, projections were made for vehicles powered by more advanced, yet still experimental batteries, viz., nickel-zinc, zinc-chloride, and lithium-sulfur. The characteristics of the various batteries are shown in Table 11. It was warned, however, that the "cost and life characteristics for zinc-chloride and lithium-sulfur batteries are relatively uncertain and the figures . . . are quite optimistic."¹⁰⁰

It was assumed that the electric cars were four-passenger subcompacts with speed and acceleration just below that of current low performance conventional subcompacts.¹⁰¹ The urban ranges for cars with lead-acid, nickel-zinc, zinc-chloride, and lithium-sulfur batteries were assumed to be 54, 144, 145 and 138 miles respectively; at a constant speed of 30 mph and on level roads, vehicle ranges would be roughly doubled.¹⁰²

Life cycle costs (1974 cents per mile) were estimated for the various electric cars and for a car powered by a conventional Otto. The results are presented in Table 12. Although the electric vehicles had an advantage in maintenance, they tended to have higher life-cycle cost than a gasoline-powered subcompact.

The cost of the battery was identified as the prohibitive factor. As a result, the report concluded that electric cars "are unlikely to approach the conventional subcompact

TABLE 11
Car Battery Characteristics

Type	Lead-Acid	Nickel-Zinc	Zinc-Chloride	Lithium-Sulfur
Weight, lbs	1500	1080	570	300
Available Energy, kwh/lb	13	44	70	140
Energy Efficiency, Percent	46	66	70	62
Life, Years	1.3-3.4	5.8	7.3	3-5
Cost, 1973 Dollars	1200	4380	600	600

Source: General Research Corporation, "Impacts of Electric Car Use in St. Louis, Philadelphia and Los Angeles," May 1975, p. 3.

TABLE 12

Life-Cycle Costs (1974 cents per mile),
Electric Cars versus Otto-Powered Subcompact

	Otto Sub- Compact	Lead- Acid	Nickel- Zinc	Zinc- Chlorine	Lithium Sulfur
Depreciation					
Vehicle	2.4	2.7	2.7	2.7	2.6
Battery	0	4.0-10.3	5.6	0.9	1.3-2.2
Upkeep	2.5	1.5	1.2	1.2	1.2
Fuel ^a	1.2	2.8	1.8	1.5	1.6
Pollution Control	0.9	0	0	0	0
Financing	1.6	2.9	4.1	2.4	2.4
Taxes, etc.	4.3	4.5	4.5	4.5	4.5
TOTAL	13	18-25	20	13	14-15

^aFuel costs assumed to be \$.40 per gallon gasoline, \$0.036 per kilowatt electricity.

Source: General Research Corporation, "Impacts of Electric Car Use in St. Louis, Philadelphia, and Los Angeles," May 1975, p. 12.

in overall economy until battery development drastically reduces battery depreciation costs."¹⁰³

The GRC report implied that a rise in the price of gasoline relative to electricity would favor electric cars. However, it appears that the increase would have to be very large, something on the order of 500%, before electric cars with lead acid or nickel-zinc batteries could be competitive with Otto-powered subcompacts; assuming the successful development of zinc-chloride and lithium-sulfur batteries, a much smaller increase in the relative price would be needed.

b. Ford

According to engineers at Ford's Electric Systems Department,

. . . electric vehicles cannot achieve the performance characteristics of the American IC engine-propelled cars of the intermediate and larger classifications without severe limitations in vehicle driving range. However, reasonable driving range is feasible for vehicles of the lower performance hue in the American passenger car spectrum and for delivery vehicles.¹⁰⁴

Estimates of lifetime costs per mile were made for electric cars powered by lead-acid batteries and ones driven by the much more advanced, but still experimental, sodium sulfur batteries; these figures, and ones for comparably sized Otto-powered cars are presented in Table 13.

The high initial cost of electric vehicles, due primarily to the expense of the batteries, resulted in higher lifetime costs for the electric vehicles despite the lower fuel cost. The report cautioned, however, that an "accurate comparison" is not possible since fuel costs for gasoline

TABLE 13

Comparison of Per Mile Cost,
Electric Cars and Otto-Powered Subcompact

	Vehicle Costs - Cents/Mile				
	Subcompact		Compact		
	ICE (1)	Electric (45 HP) (2)	Electric (35 HP) (2)	ICE (1)	Electric (3)
1. Vehicle Initial Cost (Inc. Drive Tr.)	2.1	3.3	3.2	2.7	6.8
2. Electrical Power Train Initial Cost		1.3	1.2		4.2
3. Fuel Cost ⁽⁴⁾ (excluding taxes)	1.4	1.1	0.9	1.8	1.3
4. Maintenance (including battery replacement)	2.1	3.2	2.9	2.2	0.7
5. Total (Items 1, 3, 4)	5.6	7.6	7.0	6.7	8.8
(1) From U.S. Department of Transportation Publication, 5/4/72					
(2) Lead-acid battery					
(3) NaS battery					
(4) Fuel costs for the electric vehicles are based upon driving the Ford Suburban Economy Route					

Source: Ford Motor Company, "Electric Systems Department, Electric Vehicle Systems Study," SR-73-132, October 1973, p. 177.

were based on data from the 1960's while those for electric power were from the early 1970's.¹⁰⁵ This would appear to create a bias against the electric vehicles.

Ford offered a more complete comparison of electric and gasoline car costs in another study.¹⁰⁶ A hypothetical 1974 Pinto, alternatively equipped with a lead-acid or lead-cobalt battery was compared to the conventional production version. Unit fuel prices were assumed to be 70 cents per gallon for gasoline and 3 cents per kilowatt hour for electricity.

The results are shown in Table 14. While fuel costs for the electric vehicles were lower than those of the conventional cars, this advantage was more than offset by higher battery amortization and vehicle depreciation charges. Thus Ford's conclusions on the practicality of electric vehicles were unencouraging:

Tremendous gains in electric storage batteries, . . . are needed before electric cars can achieve the same cost of ownership as gasoline cars in an urban passenger car duty cycle. When cost parity is attained, the utility of electric cars will remain uncompetitive due to their limited range.¹⁰⁷

c. Chrysler

Chrysler's experience with electric cars has not been as extensive as G.M.'s or Ford's. Chrysler stated the electric vehicle's biggest problem is the battery and that "the batteries available today are heavy, have limited capacity, and disappointing performance."¹⁰⁸ According to the firm, however, the electric car someday may serve "as a small commuter car with restricted range."¹⁰⁹

TABLE 14
Annual Cost of Ownership
5-Year Period, 10,000 Miles Per Year

	1974 Pinto (Gasoline)		Pinto Size Electric Car	
	City	City/Suburban	Lead-Cobalt Battery	Lead-Acid Battery
<u>Fixed Costs</u>				
Depreciation	\$392	\$392	\$ 676	\$ 720
Insurance	215	215	242	245
Financing	84	84	144	154
Licensing	16	16	21	22
TOTAL FIXED COSTS	\$707	\$707	\$1083	\$1141
<u>Variable Costs</u>				
Fuel	434 ^a	372 ^b	136	136
Scheduled Maintenance	83	83	213	570
Non-scheduled Maintenance	26	26	10	11
Tires	66	66	73	79
Tolls and Parking	30	30	30	30
Washing and Waxing	30	39	30	30
Collision Expense	25	25	25	25
TOTAL VARIABLE COSTS	\$695 ^a	\$632 ^b	\$ 517	\$ 881
TOTAL AVERAGE ANNUAL COST OF OWNERSHIP	\$1402 ^a	\$1339 ^b	\$1600	\$2022
^a 16.1 mpg				
^b 18.8 mpg				

Source: Ford Motor Company, "Analysis of the EFP Electrical and Electric Passenger Car Battery," CRM-74-2, June 1974.

d. Eaton

Electric power was not considered worthy of evaluation in the Eaton study: "Electric vehicles were . . . discounted due to the state of technology being woefully inadequate and the economics generally unattractive."¹¹⁰ Eaton added that it is the world's largest producer of electric vehicles (electric forklift trucks) and its expertise in this area is considerable.

e. JPL-1975

In its analysis JPL reported on the range and speed characteristics of a number of electric vehicles that were built during the late sixties and early seventies.

As Table 15 shows, these cars are inferior to the Otto-powered car in both range and speed. JPL concluded that "the flexibility and convenience of electric vehicle operation is presently inferior to that of the conventional automobile and promises to remain so in the foreseeable future."¹¹¹

In the area of energy consumption, electric vehicles appeared in a somewhat better light:

The energy economy of lead-acid powered electric cars is presently competitive or slightly superior to that of conventional cars so long as their design range lies within their region of economical operation, e.g., 30-50 miles. Attempts to "force" design range beyond this region by increasing battery weight result in a sharp reduction in energy consumption (sic) with very little improvement in range.¹¹²

Air pollution due to electric vehicle use "may be significant, small, or nonexistent, depending on whether the

TABLE 15
 Characteristics of Electric Cars Built During 1960's

	Maximum Speed, mph	Range, mi.
Comuta	40	37 at 25 mph
GM 512	40	47 at 30 mph
Sundancer, ESB	--	70-75 on SAE residential
Marquette, Westinghouse	25	50
Henney Kilowatt, Union Electric	40	40
Yardney	55	77
Alllectric, West Penn Power Co.	50	50
"Nini" GE	55	100 at 40 mph
American Motors and Gulton Ind.	50	150 with regeneration
ESB, Renault	40	25-35
Rowan Electric	40	100
Alllectric II, West Penn Power Co.	50	50
Super-Electric Model A, Carwood and Stelher, Ind.	52	--
Cortina, Estate Car	60	39.9 at 25 mph
Comet Ford	70	--
City Car Pinto	50	29 at 40 mph
Mars II, Electric Fuel Propulsion, Inc.	60-65	70-120
Electrovair, GM	80	40-80
Electrovan, GM	70	100-150
Allis Chalmers, Karmann-Chia	--	60 at 60 mph
Chrysler-Simca	--	40
Electric Fuel Propulsion, Inc.	85	150-175
Falcon, Linear-Alpha	60	75 at 80 mph

Source: Jet Propulsion Laboratory, Should We Have a New Engine?, 1975, Vol. 2, pp. 8-7, 8-8.

source of electric generating plant energy is coal, oil, or non-fossil (e.g., nuclear) fuel."¹¹³

Regardless of the original source of electricity, the per-mile emissions of CO and HC of electric vehicle operation would be "negligible compared to the Federal automotive standards."¹¹⁴ In comparison to Otto-powered cars, electric vehicles would emit higher levels of NOx, sulfur dioxide, and particulates if electricity were generated in oil-fired plants and still higher levels of these pollutants if coal-fired plants were involved. No air pollution at all would be created if nuclear power was used; however, there would be the problem of radioactive wastes.

Despite the equal or perhaps slightly better energy consumption of low range electric vehicles, the JPL estimated that "initial and life-cycle cost of electric vehicle ownership is presently greater than that of conventional cars."¹¹⁵ The high cost of battery replacement and the fairly short lifetimes of contemporary batteries were cited as the critical negative factors: "A breakthrough," concluded the JPL, "in battery . . . technology is needed before electric vehicles can be expected to capture a significant fraction of the automotive market."¹¹⁶

f. MIT

According to the MIT study, "private cars with current or near-term battery technology are unlikely to be competitive with conventional cars unless massively subsidized."¹¹⁷

Cost per mile for electric vehicles powered by either current lead acid batteries or the somewhat more advanced nickel-zinc battery, were estimated to be higher than that of a typical Otto-powered car (see Table 16).

An important point made in this study is that "the nominal EV ranges commonly quoted are gravely misleading as an indicator of 'guaranteed range' which a user of the vehicle can be confident of obtaining on a particular day's travel."¹¹⁸ Cold weather, wet roads, and strong headwinds would diminish the vehicle's range and acceleration; moreover, the performance of the vehicle would deteriorate as its aging batteries gradually lost their capacity to store energy: "Indeed," it is stated, "we doubt that a vehicle with a 50-mile nominal range can, in fact, be guaranteed to deliver 10 miles, since it is easy to specify a combination of not extreme conditions under which the car will obtain an actual range of only 20% of nominal."¹¹⁹

Thus, a major conclusion of the MIT study:

It is clear that no substantial market for electric passenger cars exists with current technology, even with gas prices in the range of \$1.20 per gallon. There is no need to frame a theoretical argument to make this point. One need only look at the situation in Europe and Japan, where (due to high taxes on fuel) gasoline prices have approximated such levels for some years, and where driving distances are shorter than in the U.S., and where (nevertheless) no market for electric passenger cars has developed.¹²⁰

g. JPL-1978

No evaluation of electric vehicles is made in this study.

TABLE 16

Estimated Costs for Electric Vehicles

Power Source	Cost ¹ (¢/mile)	Comment
Gasoline	13-15	Today's technology
Lead-acid battery	18-25	Nominal range, 54 miles
Nickel-zinc battery	20	Nominal range, 144 miles
Lithium-sulphur battery	14-15	Nominal range, 145 miles

¹Based on electricity at 3.6/kwh and gasoline at 50¢/gallon (including tax). The numbers are in 1973 dollars.

Source: Massachusetts Institute of Technology, Energy Laboratory, "Federal Support for the Development of Alternative Automotive Power Systems," 1976, p. 277.

12. Gas Turbine

The gas turbine, unlike the powerplants already considered, has never been used in cars sold to the public. During the mid-1970's, the turbine was in the advanced development stage and was not available for immediate use in production automobiles. Nevertheless, it had been sufficiently developed so that its potential could be reasonably evaluated.

a. General Motors

In 1977, tests of G.M.'s latest experimental gas turbine resulted in fuel economy figures (for a 4000 lb. sedan) of 12.0 mpg in city driving and 20.4 mpg on the highway; in comparison, G.M.'s 1977 model year cars of equal weight had better fuel economy in the city and roughly the same fuel economy as the turbine in highway driving.¹²¹

G.M. found that the turbine could, at least in the laboratory, meet even the most strict federal emissions standards now on the books. In comparison with the standards for 1981 of 0.41 gpm HC, 3.4 gpm CO, and 1.0 gpm NOx, the experimental G.M. turbine emitted 0.02 gpm HC, 2.5 gpm CO, and 0.32 gpm NOx and did so with no exhaust treatment device.¹²²

G.M. stated that the turbine is "significantly" more expensive to produce than the conventional Otto. The higher cost was due to the materials needed for the engine's high temperature regions and that "many of the processes

currently used for turbine engine parts do not lend themselves to volume production."¹²³

b. Ford

Like G.M., Ford has demonstrated the ultra-low emissions capability of the gas turbine.¹²⁴

Ford's turbine research group made the following projection for the single-shaft type of turbine engine.¹²⁵ First, Ford projected a slightly better 0-60 mph acceleration with the turbine in comparison to the conventional Otto; however, the turbine's response is apt to be slightly more sluggish during the first four seconds of acceleration. Second, Ford estimated the fuel economy of the turbine to be approximately 40% greater than a comparable Otto. Third, this turbine, if constructed of metal parts only, would be slightly higher in production cost than the Otto; if ceramic materials were successfully developed for the turbine's hot parts, the cost of the turbine would be approximately equal to the Otto's. Finally, Ford estimated that the turbine's weight would be roughly equal to that of the conventional Otto. Ford warned, however, these projections were optimistic and not guaranteed and, hence, should be taken with caution.

In another publication, Ford noted other apparent advantages of the gas turbine: increased durability, less vibration, and, because it has fewer moving parts than the conventional Otto, it is easier to service.¹²⁶

c. Chrysler

Chrysler's work in this area has been focused on the free-turbine (and all-metal) configuration. Chrysler considered this engine's potential as a "production candidate" to be "marginal." In comparison to the Otto, it would have "little or no fuel economy advantage."¹²⁷ Moreover, high production costs of the turbine, according to the firm, "remains a serious obstacle to widespread acceptance of the gas turbine in general passenger car usage."¹²⁸

On the other hand, Chrysler described the turbine's low emissions, multi-fuel capability, and reliability as attractive.

Chrysler implied that the future of the gas turbine will probably depend on whether low cost ceramic materials can be successfully developed.

d. Eaton

Eaton concluded that the gas turbine was superior to the conventional Otto in emissions, weight, maintenance, and smoothness; the turbine was described as comparable to the Otto in noise and size. Flexibility of the free-turbine type was called "very favorable," while that of the single-shaft configuration was called "unfavorable." It was not clear whether the gas turbine would be more or less durable than the conventional Otto.

According to Eaton, the gas turbine's production cost and fuel economy, relative to the conventional Otto's

depended on the availability of structural materials, especially ceramics:

Turbine engines require the use of substantial amounts of expensive, difficult to fabricate superalloy and an expensive regenerator. Potentially possible, but requiring a great development effort, is a simpler turbine operating at higher pressure ratios and temperatures using lower cost ceramic materials. Such an engine could ultimately be cheaper than the piston engine. Single-shaft engines cost significantly less than two-shaft, but require more sophisticated and costly transmissions.

The turbine has higher fuel consumption, especially at light loads typical of much automobile operation. At very tight emission standards, the fuel consumption increase of piston engines could result in the disadvantage of the turbine being eliminated. Development of materials allowing operation at higher temperature would help make the turbine competitive on fuel consumption. The turbine is capable of operating on a wide range of fuels, but specific designs require a limited range.¹²⁹

e. JPL-1975

JPL's mature version of the gas turbine (referred to in this report as the Brayton engine) is all-metallic; both the single-shaft and free turbine configurations were considered. The use of ceramic parts was considered impractical under current technology.

JPL foresaw no emissions problems with the gas turbine. Although it was noted that turbines sound different than the conventional Otto, no difference in overall quietness was expected. Differences in acceleration response were projected with the gas turbine being somewhat more sluggish than the conventional Otto at low vehicle speeds but having greater acceleration at higher speeds. It was expected that

the gas turbine would be easier to start, especially in cold weather.

In comparison to a \$660 unit manufacturing cost for the conventional Otto, the JPL report estimated a unit cost of \$691 for the single-shaft type and \$809 for the free turbine type. The higher unit cost of the gas turbines was largely due "to the requirements for superalloys and stainless steels in the high temperature areas of the engine."¹³⁰

Despite the higher initial cost, the report concluded that the lifetime operating cost for the turbine would be significantly lower than that of a comparable Otto (see Table 5). A fuel economy advantage between twenty and thirty percent was projected for the turbine; also the turbine's maintenance cost was expected to be much lower than a comparable Otto.¹³¹

f. JPL-1978

No major obstacles in component technology, according to this report, remained to prevent the final development of all-metal gas turbines. Significant progress, however, was still needed before better turbines using ceramic parts could be practical.¹³²

Better fuel economy than that of a comparable conventional Otto was projected for both types of turbines (see Table Two). The multi-fuel capability of the gas turbine was also attractive.

In the area of emissions, it was stated that the gas turbine would have no problem in meeting the most strict standards currently scheduled for HC and CO. The meeting of the 0.4 gpm standard for NOx, however, would require more development.

Unit variable costs for the free-turbine type were estimated to be forty to fifty percent greater than those of a comparable conventional Otto. No information on lifetime operating costs was offered.

13. Stirling Engine

a. General Motors

G.M. predicted very high fuel economy for the Stirling engine, at least under steady-state conditions (see Table 17).

Emissions of HC and CO were called "extremely low," while NOx emissions were found to be "high" although "sufficient research and development might bring them down to acceptable levels."¹³⁴

Although the engine's major components appeared durable, the permanent sealing of the gaseous working fluid seemed difficult. Moreover, G.M. reported that the engine was heavy and bulky and would be expensive to produce.

G.M. concluded that "although some of these disadvantages may respond to further research and development, others do not suggest that promise."¹³⁵

TABLE 17

G.M. Estimates of Stirling Engine Fuel
Economy in Small, Compact and Large Cars

	Max Hp	Urb F.E. mpg	Hwy F.E. mpg
Small Stirling	67	35.4	36.7
Small Otto	82	23.3	30.0
Compact Stirling	100	27.7	30.4
Compact Otto	102	16.7	20.5
Large Stirling	182	17.7	21.2
Large Otto	188	10.9	14.0

Source: General Motors Corporation, "General Motors' Analysis of Jet Propulsion Laboratory Report, 'Should We Have a New Engine?', " November 1975.

b. Ford

Extremely low levels of emissions for all three types of federally controlled pollutants were demonstrated in bench test at Ford.¹³⁶

Acceleration of a Stirling-powered car was considered to be about the same as that of a comparable Otto-powered car.

In comparing the fuel economies of the Stirling with a large production V-8, Ford estimated a 37% advantage for the Stirling. The multi-fuel capability of the Stirling was also pointed out.

Test showed that the Stirling made significantly less noise than current car engines.

On the other hand, it appeared that the Stirling would take somewhat longer to start than conventional engines.¹³⁸ The two major problems with the Stirling, according to Ford, are the engine's power density (power per unit of weight) and its complexity.¹³⁹ Presumably, these problems put the Stirling at a disadvantage in unit manufacturing cost.

c. Chrysler

Chrysler's experience with the Stirling has not been great. The firm's evaluation of the engine, as of 1976, was as follows:

Current Stirling engine concepts utilize hydrogen gas at 3000 psi as a working fluid. The development of adequate sealing of this gas, especially in a mass production application, will be a monumental engineering challenge. Maintaining satisfactory engine

response by controlling the amount of dead volume within the engine or by varying the pressure level of the working fluid will similarly be a major challenge. However, because of the engine potential: excellent fuel consumption, especially at light load; quietness; and the use of clean burning continuous combustion with broad cut fuels, we believe that it is an excellent candidate for alternative engine development.¹⁴⁰

d. Eaton

The Stirling received high marks for smoothness, quietness, durability, and flexibility. Eaton reported that the engine had the lowest emissions of all known powerplants and had a potential for having the highest fuel efficiency.

On the other hand, Eaton stated that the "Stirling appears to have a cost disadvantage due to the requirement for high temperature alloys in the heater head and to control problems."¹⁴¹

Nevertheless, it was concluded that "on balance, the Stirling engine appears the most attractive powerplant over the long range."¹⁴²

e. JPL-1975

In comparison to equivalent Otto-powered cars, JPL estimated that vehicles with mature Stirling engines would have 44% better fuel economy on the highway and 49% better fuel economy in the city.¹⁴³ Moreover, it was predicted that the Stirling would easily meet the strictest emission standards now envisioned. No problems with

currently unregulated emissions were seen. The Stirling was expected to be a quieter engine than the Otto.

On the other hand, it was expected that the Stirling would take somewhat longer to start operation after ignition.

A more serious disadvantage was expected to be cost: the JPL projected a unit manufacturing cost of \$820 for the Stirling; this figure exceeds the estimated cost of a comparable Otto by \$260.¹⁴⁴

Despite the higher initial cost to the consumer, however, it was concluded that the lifetime ownership cost of the Stirling would be much lower than that of the conventional Otto (see Table 5). The lower lifetime cost of the Stirling was attributed to less maintenance and better fuel economy.

f. MIT

In its evaluation of the Stirling engine, the MIT study considers the characteristics of a "first generation system" (FGS); this engine is assumed to be the production version of the prototype configurations of the mid-1970's. By the mid-1970's the Stirling prototypes had "reached the development status where questions of their performance have been largely resolved,"¹⁴⁵ and hence, may be used to project short term improvements. In essence, the first generation system concept is the same as the "mature" engine concept of JPL.

The first generation Stirling was rated as much better than the conventional Otto in emissions, fuel economy, smoothness, noise. In other areas, such as weight, durability, maintenance, and driveability, the Stirling was expected to be competitive with the conventional Otto. A slightly longer start-up time was expected, however.

High manufacturing cost was seen as the Stirling's major drawback:

. . . at this time it appears that the initial cost of the FGS, if it were manufactured in sufficient quantity to utilize the available economies of scale, would be one to several times that of a comparable"

conventional Otto.¹⁴⁶

g. JPL-1978

This study repeats the conclusions of the first JPL report and the MIT report. Upon successful refinement of current prototypes, the Stirling should have significantly better fuel economy than the then-present version of the conventional Otto (an advantage of up to 40%) and at the same time have extremely low emissions, low noise levels, etc.¹⁴⁷

Again, the JPL projected a much higher production cost for the Stirling and this would make Stirling-powered cars \$800 (1977 dollars) more expensive than their Otto-powered counterparts.¹⁴⁸

14. Conclusions on Type III Suboptimization

The results are ambiguous. Each alternative had at least one disadvantage when compared to the conventional Otto. On the other hand, there was no powerplant that was inferior to the conventional Otto in every way. In short, the evidence neither fully supports or denies the existence of Type III suboptimization.

But does the bulk of the evidence suggest anything? It is clear that the conventional Otto retained its traditional advantage of low production cost. For an alternative to raise either producer or consumer surpluses, it must have a marked advantage in some other characteristic. Fuel economy has probably become the most important powerplant characteristic other than initial cost, or, at least, the one that has risen most in importance in recent years. Those powerplants with better fuel economy, therefore, should have become more attractive to both firms and consumers.

All sources show a fuel economy advantage for the Diesel and Stirling engines. As of the mid-1970's, however, the Stirling was still in the prototype stage; the fuel economies of production versions are based on guesses of near-term improvements and, as a result, are open to speculation. In the interest of finding the most likely case of Type III suboptimization, the Stirling is therefore set aside.

This leaves the Diesel. The failure of the American producers to offer Diesel-powered cars until the end of our

test period is a plausible case of Type III suboptimization. This conclusion is supported by the use of foreign Diesel cars in U.S. during the mid-1970's. In 1972, foreign Diesel sales were about 6,000 units; by 1976 this figure had risen by 350% to a level of 21,000 units. The growth of foreign Diesel sales is even more remarkable since much of it took place when the sales of Otto-powered cars were depressed.

It can be argued, therefore, that G.M.'s entry into the Diesel field at the end of 1977 was belated. Especially notable is that G.M.'s introduction of the Diesel was not contingent on the building of factories in the U.S., since the foreign Diesels could have been countered with "captive imports" from G.M.'s Opel division in West Germany.

A couple of qualifications are in order, however. First, the period of this possible suboptimization was not long. It is possible--perhaps likely--that G.M.'s European capacity for Diesel cars was too pressed to supply the U.S. market. Consequently, new capacity, either in the U.S. or abroad, would have to be built to satisfy the growing demand for Diesels. The first strong sign that Diesels might be profitable in the U.S. was the great jump in crude oil prices in the fall of 1973. If G.M. had set its plans in motion at that time, and had carried out those plans at a normal pace, Diesels could have been offered no later than the end of 1976. One year, therefore, appears to be the approximate length of the delay of an American Diesel car.

The second qualification has to do with government policy. On the one hand, uncertainty about the final level of the NOx emissions standard discouraged introduction of Diesel cars. If Congress decided to stick with the original provision of the Clean Air Act (0.4 gpm of NOx), the law would have prevented introduction of the Diesel; the issue remained unsettled throughout the 1970's, however. Consequently, American producers were justifiably reluctant to commit themselves to Diesel production.

On the other hand, the introduction of an American Diesel was probably hastened by the federal fuel economy standards of 1975. With its traditional emphasis on larger cars, G.M. had to make great changes in the product mix to satisfy the standards; as a result, a commitment to the fuel-thrifty Diesel became much more attractive. Moreover, a commitment to Diesel cars might give the firm added leverage in its efforts to get Congress to relax the NOx standards for all cars.

In short, it is unclear whether federal policy delayed or hastened the introduction of an American-built Diesel car.

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142. Ibid., p. 8.

143. Jet Propulsion Laboratory, Should We Have a New Engine?, op. cit., vol. 2, p. 6-7.
144. Ibid., p. 6-26.
145. Massachusetts Institute of Technology, op. cit., p. 130.
146. Ibid., p. 139.
147. Jet Propulsion Laboratory, "Automotive Technology Status and Projections," op. cit., vol. 2, chps. 4, 9.
148. Ibid., p. 9-70.

CHAPTER IV

THE RATE OF DEVELOPMENT OF ALTERNATIVE AUTOMOTIVE POWERPLANTS DURING THE MID-1970'S

1. Introduction

The purpose of this chapter is to evaluate the rate of development of alternative powerplants during the mid-1970's. It is of interest here to discuss whether powerplant technology was produced efficiently and whether the observed rate of technology production was at the socially optimal level. In other words, this chapter deals with Type I and Type II suboptimization.

The available evidence is of little help in evaluating the extent of Type I suboptimization; this discussion, therefore, is deferred to the end of the chapter. The discussion of Type II suboptimization, which is presented next, assumes that Type I suboptimization is absent.

In the previous chapter, the state of technology in the powerplant field was reviewed. Moreover, it gave an idea of the technological opportunities that automakers could exploit. To be sure, it is unclear what the powerplant of the future will be. It may very well be that a number of powerplants will someday be in widespread use: small utility vehicles may be electrically powered, some passenger cars may have either the conventional Otto, stratified charge, Diesel or Stirling engines, while other cars and larger vehicles may have Stirling or gas turbine engines. However, it is clear that the technological opportunities are not extremely limited, as they appear to be in, say, the stone and salt industries. Indeed, as Roger B. Smith, executive vice-president of G.M., put it, "I don't think you will find anybody in G.M. who is not convinced that by 2000 we will have some alternative powerplant."¹ The efforts to exploit the opportunities for innovation in the powerplant field are now reviewed.

2. The Efforts of Automotive Technology Producers in the Development of Alternative Powerplants

a. The Automakers

Data on the Big Three's R&D expenditures on alternative, unconventional powerplants are presented in Table 18. A steady increase in expenditures took place between 1967 and 1973. After 1973, however, it appears that the industry's efforts leveled off and declined. The

TABLE 18

G.M., Ford, and Chrysler
R&D Expenditures on Alternative Unconventional Powerplants
(in millions of current dollars)

Year	G.M.	Ford	Chrysler
1967	1.94	4.8	n.a.
1968	5.09	4.9	n.a.
1969	9.17	6.6	n.a.
1970	12.0	8.0	0.1
1971	20.1	13.0	0.3
1972	22.2	20.3	0.8
1973	35.2	31.6	3.6
1974	35.0*	23.1*	1.7*
1975	34.1*	19.0	n.a.
1976	26.4*	n.a.	n.a.
1977	27.0*	n.a.	n.a.

* - company estimate

n.a. - not available

Sources: Chrysler Corporation, "Request for Suspension of the 1977 HC and CO Emission Standards," January 1975; Ford Motor Company, "Application for Suspension of 1977 Motor Vehicle Exhaust Emission Standards," January 1975; General Motors Corporation, "General Motors Request for Suspension of 1977 Federal Emission Standards," January 1975; Ford's expenditures for 1975 from U.S. Congress, Senate, Committee on Commerce, Hearings on Automobile Fuel Economy and Research and Development, March 1975, p. 162.

figures are derived from company sources in 1975 and, as a result, most of the figures for 1974 to 1977 are not actual expenditures but corporate estimates. However, a review of industry trade journals since 1975 reveals no major new commitment by the automakers to develop alternative powerplants.

During this period, each of the Big Three experimented with a number of alternative powerplants. In 1975, for instance, G.M. had work in progress on the Diesel, stratified charge, gas turbine, rotary, and electric powerplants;² Ford reported research on the stratified charge, Diesel, gas turbine, Stirling, and electric powerplants;³ the stratified charge, Diesel, and gas turbine engines were part of Chrysler's efforts in that year.⁴

The evidence on American Motors is scanty, but it does appear that, other than some work in the rotary engine, AMC supported little research on alternative powerplants during the mid-1970's.

Each of the Big Three, therefore, had a portfolio of powerplant projects; moreover, the number of projects in each portfolio tended to vary directly with firm size. The automakers were hedging their bets by avoiding a full-blown commitment to any one powerplant. Information on expenditures per powerplant is not available for G.M. and Ford; figures on some of Chrysler's projects are available, however (see Table 19).

TABLE 19

Data on Chrysler Powerplant
R&D Expenditures
(thousands of dollars)

	1973	1974	1975	1976	1977	1978
Conventional Otto	--	--	--	10,695	17,542	26,178
Pre-Chamber Stratified Charge	480	225	325	--	200	500
Diesel	--	--	--	1,257	1,515	3,800
Gas Turbine	2,900	1,300	1,110	--	--	--

Sources: U.S. Congress, House, Committee on Science and Technology, Inventory of Energy Research and Development: 1973-1975. Committee Print, 94th Cong., 2nd sess., January 1976; vol. II, pp. 1982-2034; U.S. Congress, House, Committee on Science and Technology, Inventory of Advanced Energy Technologies and Energy Conservation Research and Development, 1976-1978, 96th Cong., 1st sess., January 1979, vol. III, pp. 2318-2383.

While the quantitative data are scanty, it is safe to say that the automakers have concentrated their efforts on improving the conventional Otto. The principal investigator for the 1975 JPL study stated that "over ten times as much money was going into work to improve the conventional engine than into alternative engines."⁵ Data from G.M., however, indicate a lower ratio of conventional to alternative powerplant expenditures, something on the order of only two to one; G.M.'s failure to include fuel economy expenditures in its data probably biased the proportion downwards.⁶

b. Other Technology Producers

It is impossible to come up with an exact number of technology producers, in addition to the automakers, who were active in powerplant development during the 1970's. A rough, and probably conservative guess, puts the number around one hundred. These producers included traditional automotive vendors, oil companies, and high technology inventor-firms; in size they ranged from industrial giants such as General Electric and Texaco to tiny, family-run enterprises.⁷ Moreover, during the second half of the 1970's, the production of powerplant technology at universities and government-owned laboratories became significant.⁸

c. The Observed Rate of Powerplant Technology Production

Good data on the rate of powerplant technology (with R&D expenditures as a proxy), summed over all

technology producers, are impossible to obtain. However, some idea of the total expenditures on powerplant technology may be gained by referring to two reports on energy research and development in the U.S. prepared by the Oak Ridge National Laboratory.⁹ This information is summarized in Tables 20 and 21. The Oak Ridge Labs claimed that the surveys covered between 80-85 percent of organizations doing energy R&D; only projects with funding of \$5,000 or more per year were included. Some organizations responded with descriptions of their research projects but withheld information on the level of funding.

Other points should be kept in mind when examining the various energy categories in the tables. First, the internal combustion category includes work on the conventional Otto, the stratified charge Otto, the Diesel, rotary, and the gas turbine. The external combustion systems category included, between 1973 and 1975, development of the Rankine and Stirling engines; after 1975, work on alternative fuels, flywheels, and engine hybrids were added to this category. The electric-powered systems category refers to work involving the integration of electric vehicle components; the battery energy category includes much work for non-automotive applications.

TABLE 20

Reported R&D Expenditures in the U.S.
on Powerplant Technology, 1973-1975
(thousands of dollars)

Energy Category	1973 \$	1974 \$	1975 \$
Internal Combustion Systems	32,065	41,320	39,922
External Combustion Systems	6,777	4,364	4,515
Electric-Powered Systems	5,442	7,788	5,880
Batteries	13,796	15,416	19,572

Source: U.S. Congress, House, Committee on Science and Technology, Inventory of Energy Research and Development: 1973-1975, Committee Print, January 1976, Vol. V, Table 4.

TABLE 21

Reported R&D Expenditures in the U.S.
on Powerplant Technology, 1976-1978
(thousands of dollars)

Energy Category	1976 \$	1977 \$	1978 \$
Internal Combustion Systems	93,492	147,969	167,795
External Combustion Systems	5,546	7,471	22,481
Electric-Powered Systems	1,346	56,522	14,753
Batteries	21,505	37,695	57,329

Source: U.S. Congress, House, Committee on Science and Technology, Inventory of Advanced Energy Technologies and Energy Conservation Research and Development: 1976-1978, Committee Print, 1979, Vol. III, Table 3.

3. Government Policy and Its Impact on the Rate of Development of Alternative Powerplants During the 1970's

Strictly speaking, the federal government has been involved in the production of automotive technology for many years. One of the earliest instances of government-supported work was the Bureau of Mines' activity of the early 1920's in identifying some of the causes and components of automobile exhaust gases. During the post-World War II era, the Department of Defense sponsored a host of research projects on batteries and engines for military vehicles. The space program promoted further activity, especially in advanced batteries and related electronic components.

In 1969, federal effort turned to powerplant technology more directly related to passenger cars. Between 1969 and 1974, roughly 35 million dollars were spent to develop alternative automotive fuels and power systems; the expenditures were handled by the Environmental Protection Agency and for the most part were spent in research contracts with private firms (see Table 22). At that time, clean air, not energy, was the chief concern, and consequently nearly half of the EPA's monies went to the development of the Rankine engine.

After 1974, federal activity in the powerplant field shifted to the newly formed Energy Research and Development Administration; in 1978 ERDA, along with its powerplant programs, was absorbed into the new Department of Energy.

As Table 23 indicates, federal expenditures on powerplant development rose sharply after 1974. The federal

TABLE 22

EPA Funding for Alternative Automotive
Fuels and Power Systems, Fiscal Years 1969-1974
(millions of dollars)

Category	Expenditures
Rankine cycle systems	17.267
Brayton cycle systems	10.169
Diesel cycle systems	.060
Stratified charge	.798
Heat engine/flywheel systems	.642
Heat engine/electric systems	1.124
Battery powered electric systems	1.166
Improved energy conversion and utilization subsystems	.423
Alternative fuels programs	1.229
Federal Clean Car Incentive Program	.050
Annual status of technology documentation	.470
Research grants	.848
Engineering support	1.189
TOTAL	35.445

Source: U.S. Environmental Protection Agency, Alternative Automotive Fuels and Power Systems Research and Development Programs: Summary of Fiscal Obligations; June 1974, p. A-7.

TABLE 23

ERDA/DOE Expenditures
on Alternative, Unconventional Powerplants,
Fiscal Years, 1975-1978
(in thousands of dollars)

1975	14,112
1976	23,200
1977	59,290
1978	65,000

Sources: U.S. Congress, House, Committee on Science and Technology, Automotive Transport Research and Development Act of 1976, 94th Cong., 2nd sess., House Report 1169, p. 16; U.S. Congress, Senate, Committee on Energy and Natural Resources, Hearings on Energy Conservation and Regulations in the President's Budget, 95th Cong., 2nd sess., March 1978, p. 165.

effort was designed to supplement privately supported work by concentrating on the gas turbine, Stirling and electric powerplants; as was noted in the last section, these alternatives were receiving much less attention from the private sector than the various internal combustion engines. As of 1978, about eighty percent of the federal monies were spent in contracts with private sectors.¹⁰

4. The Test for Type II Suboptimization

In a world where knowledge of the present and future is perfect, a test for Type II suboptimization would be easy to construct: the current rate of technology production is compared with that which maximizes the discounted net benefits to society.

In the real world no such precise test can be conducted. The future benefits and costs of invention can only be guessed at. The best that can be hoped for is an estimate of the proper order of magnitude of new technology production.

Furthermore, the test for Type II suboptimization should be concerned with the private market allocation of resources to the invention process: that is, the object is to study the allocative mechanism independent of government intervention. For this reason, only the period between and including 1973 and 1975 is acceptable for a test of Type II suboptimization. After 1975, the auto industry's R&D plans were greatly altered due to the federal fuel economy

standards, the provisions of which were laid down at the very end of 1975. Secondly, after 1975 there was a sharp increase in federal expenditures on powerplant development. It is not clear whether federal expenditures merely supplemented private expenditures; it is possible they have acted as a substitute for the latter or even as a stimulus. In short, after 1975, the allocation of resources to powerplant development became the result of an increasingly complex interaction of market forces and public policy.

Thus the test period for Type II suboptimization in powerplant development is between and including 1973 and 1975. The central question becomes, "Given the state of technological opportunities in the alternative powerplant field at that time, did the market allocate about the right amount of resources to the invention process?"

This question has been the subject of several studies. A report issued by the Federal Energy Administration at the end of 1974 stated that an increase in effort was needed "in order to assure an adequate, but environmentally designed personal transportation system for the Nation during the period out to the year 2000 and beyond."¹¹ The report went on to indicate the magnitude of the socially optimal level of effort:

To generate the necessary new technology, a national R&D investment of \$150 million per year for the next 25 years or so will be required. Private industry is (prior to the current economic squeeze) investing on the order of one-third the amount, concentrated in the near-term aspects of development.¹²

Two studies by the Energy Laboratory of the Massachusetts Institute of Technology also suggest that the private market was seriously underinvesting in new powerplant technology. The first report, which was issued at the end of 1974, concluded that there was:

. . . convincing justification for Federal support for R&D on alternative automotive powerplants. Some alternative engine technologies are not receiving adequate attention within the automobile industry for sound reasons which are unlikely to change; a government program can support projects which are justifiable from a public standpoint but not a private one. Such a program can make substantial contributions to national air pollution statements and fuel conservation goals by advancing the state-of-the-art of selected engine technologies and by producing the technical data necessary for developing regulations and other policies.¹³

A two to five increase over the then current level expenditures was recommended.

In the second MIT report,¹⁴ attention was focused on the benefits of public support of the development of the Stirling, Diesel, and electric powerplants; it was particularly enthusiastic about increased development of the Stirling.

Prototype Stirling engines on dynamometers have clearly demonstrated low emissions and high fuel economy relative to the present ICE. Stirling-powered vehicles have the potential to equal every other important attribute of ICE-powered vehicles; the principle uncertainty is the engine's initial cost, which will likely be in range from the cost of the present ICE to about twice that. Maintenance costs are also uncertain. At the present time [March 1976] a total professional manpower of about 230 and an annual expenditure of \$5-10 million are being committed to development of the engine; the programs are taking place almost entirely in Europe.

A crude social cost-benefit analysis for government investment in the Stirling system demonstrates substantial likely new benefits.

. . . technical and commercial success of the system could provide social benefits with a present value of billions of dollars. The technology is neither "embryonic" nor "mature," and present and likely future private development programs are in the range where incremental R&D funding probably substantially improves the probability of technical success. We conclude that government spending on the order of \$100 to \$200 million over 5 to 10 years is likely to be a very good gamble.¹⁵

According to the report, the development of electric vehicles should also be stimulated by the government:

Widely varying assessments of the acceptability of electric vehicles using the various batteries now available or under development have been published and widely quoted. Our assessment is that only the advanced batteries, which will require substantial and successful development programs before they are widely available at reasonable cost, would provide electric vehicles with a range which would bring them into consideration as possible substitutes for other than a miniscule fraction of the passenger car fleet. A number of such R&D programs are now underway, some privately and some publicly funded.

A principal social value of widespread use of electric vehicles would be the reduction of the dependence of the passenger car fleet on petroleum producers. Thus, it would presumably lower the nation's dependence on imported fuels, as electric power will be generated increasingly using domestically available fuels. Other possible advantages which are often discussed are improvements in the environmental impact associated with the passenger car fleet and the provision of a market of off-peak power. There are, however, important offsetting arguments: the availability of other means of reducing the nation's dependence on imports, the expected reductions in automotive emissions even with the continuing use of the ICE or other heat engines, and the possible use of advanced battery technology for load-levelling at the electric powerplant site rather than in widely dispersed vehicles. Our judgment is that it is not possible to reach any firm quantitative or even qualitative judgment on the potential social value of the electric vehicle. However, since we can readily imagine circumstances, which might obtain several decades from now, in which the nation might very much regret not having accelerated the development of an acceptable electric vehicle technology, and since the cost of battery R&D programs is extremely modest

compared to overall expenditures on personal transportation, we conclude that the new value of such programs is positive.¹⁶

In contrast, the MIT report concluded that "it is unlikely that there are significant gains to be realized" by government support of Diesel engine technology.¹⁷ In other words, the private sector's efforts to advance Diesel technology appeared socially adequate.

In its examination of the powerplant issue, the Jet Propulsion Laboratory concluded, in 1975, that the gas turbine (Brayton) and Stirling engines showed much promise:

Vehicles powered by Brayton or Stirling engines can reduce national automotive fuel consumption by about one-third from that of equivalent cars with conventional engines (for the same usage) and with emissions below the strictest presently legislated standards. Introduction of either of these alternatives can be accomplished without significant adverse impact on the nation's economy. One or both should be introduced as soon as these benefits can be realized in economically mass-produced hardware.¹⁸

To make introduction of these engines possible by the mid-1980's, the report stated that "a more aggressive development program, involving at least a five-fold increase over the present rate of spending, must be pursued."¹⁹ Thus the JPL report concludes that the rate of technology production falls short of the socially optimal level.

It is noteworthy that the automakers themselves agree that the level of powerplant development was too low. Each of the major automakers has stated that additional, publicly supported work would be worthwhile. G.M. indicated the following:

There is a real need today for more work to be done in such areas as combustion, materials, heat exchange, electrochemistry, catalysts and hydrogen generation and storage. Progress must be made in these areas before competitive alternative powerplants can be built to survive in the marketplace Government research of a basic type, in areas which now represent critical bottlenecks in the industry's efforts on advanced powerplants, would supplement rather than duplicate the efforts of industry and thus make real contributions to progress.²⁰

Similarly, Ford supported government-funded research on powerplants as long as "it does not duplicate work already being done by private industry."²¹

Likewise, in reference to the possibility of extending the National Aeronautics and Space Administration's activities to the automotive field, Chrysler made the following remarks:

NASA is very good at the sort of long-range basic research we need badly now.

We would like to have NASA's skill and experience. We cannot afford to follow all the directions in which research ought to be done. We have to be selective.

For example, we would like to know more about how to manipulate the burning in a cylinder or combustion chamber. We might be able to build a better stratified charge engine. We would like to know more about the wear of parts in better engines or differently designed engines. We want to know more about different shapes of turbine blades to get the best fuel and air flow through a turbine. We need lower cost materials with which we can raise cycle temperatures to even higher levels for greater fuel economy.

We believe the automotive industry is then well suited to take the results of this research, and actually design and develop engines for mass production and deliver them to the public as a part of a desirable automobile. That is the function of private industry in our country.

The most effective way of achieving an automobile--or a variety--that is clean, efficient, and economical is a thoughtful division of research and development between government and industry.²²

Finally, conclusions of the Advisory Committee on Advanced Automotive Power Systems provide evidence on Type II suboptimization. The committee, as of 1975, was attached to the Energy Research and Development Administration; its membership was made up by representatives from the Big Three, government agencies, and academia; its purpose was to advise the federal government on policy in powerplant field. Minutes of a meeting on February 13, 1975 noted the following:

It was agreed that while the automobile industry has developed the spark-ignition internal combustion engine to its present advanced state and it is working to adopt it to the new national needs and priorities, that there is an increasing need to explore alternatives to that engine. In particular, alternative approaches which are simultaneously more efficient, compatible with environmental goals, and compatible with the changing availability of various fuels. The present level of research and development activity on alternative engines is insufficient and automobile manufacturers should not be expected to fill the gap.²³

In short, the evidence strongly indicates Type II suboptimization in the production of powerplant technology. Even with the considerable uncertainties on costs and benefits, the rate of technology production, as determined by market forces, appeared to be well under the socially optimal level during the test period.

5. The Causes of Type II Suboptimization in Powerplant Technology

In section 7 of Chapter Three, the possible causes of Type II suboptimization were identified. These were (1) the inability to impose a costless system of perfect price discrimination on the consumers of the innovation, (2) externalities, (3) differences in the private and social time rates of discount, (4) uncertainty, (5) the collusive avoidance of uncertainty, and (6) monopsony in the purchase of new technology. These are now considered in the context of powerplant development.

a. Inability to Practice Perfect Price Discrimination

This problem causes Type II suboptimization in all kinds of technology; the extent of Type II suboptimization varies directly with the ratio of the producer surplus, without price discrimination, to the surplus with it; the ratio is sensitive to the elasticity of demand for the innovation and the innovation's cost function. It is unknown whether this ratio is larger for automotive technology than for other fields, say, for instance, chemicals or electronics. If it is not, and since the extent of Type II suboptimization in powerplant development is conspicuously large, a tentative conclusion is that the inability to practice perfect price discrimination is not very important. Although this conclusion may very well be in line with one's "gut" reaction, it is theoretically conceivable that it is unfounded.

b. Externalities

One reason why the observed rate powerplant development might be lower than the socially optimal one is that a firm is unable to capture, in the form of producer surplus, but a small part of the social benefits that result from innovation. Other firms might steal the new idea and begin to produce products based on it. The presence of such free riders would reduce the profit flow to a firm which took pains to develop the new technology; the extent to which this happens depends on the speed of rival imitation and the vigor of price competition in the sale of the new product. As a consequence, a firm might not have enough incentive to produce the new technology even though social benefits are considerable.

The patent laws do much to lessen the free rider problem, however. To be sure, no firm would receive a patent on a whole type of powerplant: none of the powerplants discussed are "new." Patents would be on components or design configurations; a reliable design to seal the Stirling engine's working fluid, or a durable but cheap ceramic material, or a new high energy battery, are examples of the type of innovations which are apt to pave the way for the use of an alternative to the conventional Otto. Given the leniency of the American patent laws, it is extremely unlikely that such innovations would not be found "new and useful," and therefore ineligible for patent protection.

But patents are not a perfect solution to the free rider problem. First, a patent may not be wide or general enough to secure meaningful legal control of the innovation. It is possible that the patent on a seminal innovation--an innovation that came about due to a "flash of creative genius"--may not extend to obvious variations that may be put into production by rivals at little or no added expense of development. Competent patent lawyers can no doubt reduce the likelihood of such an event. Still, the mere disclosure of information, which comes as a result of the patent grant, represents a gift to would-be rivals that may somehow aid their R&D programs. In short, the free rider problem does not disappear entirely. As far as its value as a stimulus to invention, the patent system has a second flaw: the limited duration of the grant. After 17 years of the patent's award, free riders have free reign.

That the patent laws do not entirely preclude the escape of benefits to imitators is not unique to automotive technology. Thus the question: "Is the leakage of benefits to rivals so severe as to be largely responsible for the conspicuous suboptimization in powerplant development?"

As with the inability to practice perfect price discrimination, it is impossible to answer with certainty. It seems likely, however, that the patent laws are as effective in reducing the free rider problem in the automotive field as in any other area of technology. It is perhaps noteworthy

that an examination of auto industry documents and testimony revealed no claim that inadequacies in the patent laws discouraged the development of alternative powerplants.

c. Differences in the Private and Social Time Rates of Discount

It is usually argued that the social time rate of discount is less than the private one. If this is so, projects with benefits in the more distant future tend to be slighted by firms in favor of projects with more immediate payoffs. Indeed, it is possible that firms may select projects that have a low present value to society due to the use of the higher private rate of discount.

This may be an important cause for Type II suboptimization in powerplant development. Suppose firms were constrained to spend only x dollars per year to develop a new powerplant. Some powerplants would require more effort, and more time, to develop than others; in other words, before innovation can occur, more techtills must be produced in some cases than in others owing to the different states of development of the various powerplants. Clearly, the conventional Otto is the most highly refined of the lot. Somewhat less refined are the stratified charge and Diesel; next, but perhaps not far behind in order of declining refinement, is the rotary engine. A third group in a more primitive state of development is made up of the Rankine, gas turbine, Stirling, and electric powerplants.

The powerplants differ not only in their state of refinement but in their potential profitability. Although a powerplant's profitability depends on all of its characteristics, it appears safe to say that, given the state of things after 1973, fuel efficiency, at the margin at least, is paramount. It seems that a powerplant's potential for increased fuel economy, relative to today's engines being sold to the public tends to vary inversely with the state of development. Thus if development goes as expected, the stratified charge and Diesel will be more fuel efficient than the conventional Otto; and more efficient than these two will be the gas turbine and Stirling, especially if adequate ceramic parts become available. It is more difficult to gauge the potential of the rotary engine and electric powerplants. While the former, at present, appears less fuel efficient than the conventional Otto, it has been greatly improved during the 1970's, and with use of charge stratification and ceramic parts, the rotary may become much more attractive. While electric powerplants do not seem to have the potential to compete with the various heat engines in the complete range of automotive use, they may someday be attractive in utility vehicles for local trips. Only the Rankine, it appears, can be definitely ruled out as a more fuel efficient alternative to the conventional Otto.

In short, even though the turbine and Stirling's profitability (relative to the conventional Otto) may be significant, their profit streams would begin in the relatively distant future due to their presently unrefined state of development; the same holds, although to a lesser extent, for the stratified charge and Diesel.

Therefore, the higher the rate at which the future is discounted, the less attractive the relatively unrefined powerplants appear. Thus it is not surprising that the bulk of industry's effort has been directed at developing improved versions of the conventional Otto instead of alternative powerplants. Similarly, if the allocation of effort among the various alternatives is examined, it is not surprising that the bulk of the effort has gone to the more highly refined among them, i.e., the stratified charge and Diesel.

Moreover, the greater the difference of the private over the social discount rates, the greater the underallocation of resources to projects with future benefits. An argument can be made that the difference was unusually large during the mid-1970's. It is reasonable to assume that the social discount rate varies little over time. If so, the changes in the difference between the private and social rates must be largely the result of fluctuations in the private rate.

What determines the private rate of discount? One answer is to suppose that the private rate equals "the"

market rate of interest, adjusted for inflation. The firm may take the opportunity cost of some dollar expenditure on R&D as the foregone real interest income from a loan of that amount. If acting as a lender represents the best alternative to investing in new technology, the firm would use the market rate of interest to discount the costs and profits of R&D projects.

By postwar standards, nominal interest rates were indeed high during the test period. However, the inflation rate also was high. Indeed, between 1974 and 1977, the real interest rate on three month treasury bills was negative.²⁴ Identifying the private rate of discount with the real market rate of interest does not provide a sensible explanation for Type II suboptimization.

The private discount rate, however, may have little to do with interest rates in the capital markets. Instead, it may primarily be sensitive to the current levels of profit or organizational slack. Suppose firms which demand new technology are run by utility maximizing managers and that the arguments of the managers' utility function are current profits and future profits. Here the private rate of discount is the marginal rate of substitution between present and future profits; the opportunity cost of some dollar expenditure on R&D is the foregone present profits; conversely, the opportunity cost of foregoing some dollar expenditure on R&D is the resulting increase in future profits. Assuming diminishing marginal utility, the private

rate of discount will tend to vary inversely with the level of current profits. When current profits are relatively high, the opportunity cost (measured in utility units) of an increment in R&D expenditures is relatively low; when current profits are low the reverse is true, and, as a result, managers are more reluctant to spend money on new technology.

This may have been a cause for Type II suboptimization in powerplant technology during the period in question. The R&D expenditures of the Big Three are sensitive to the level of contemporary profit. It is noteworthy that G.M.'s total R&D expenditures increased by only a small amount (relative to increases in other years) during 1974 and 1975 and even decreased from the previous year's level during 1969; in each of those years G.M.'s rate of return on equity was nearly less than one-half of the firm's average for the postwar period. The same pattern is seen at Ford during 1974 and 1975 and at Chrysler for 1970, 1974, and 1975. In short, powerplant development was probably discouraged, circa 1975, by an unusually high private time rate of discount.

Whether the automakers generally discount the future at a higher rate than firms elsewhere in the economy is unknown.

d. Uncertainty

A fourth possible cause for Type II suboptimization is uncertainty. If the costs of risky projects were borne by society, and if the members of society were very numerous, risk per member would be small. Indeed, the risk

to individual members might be negligible, which would mean that a proper social ranking of projects requires consideration only of expected net benefits. However, if the costs of risky projects were borne by a subset of society, viz., managers and stockholders of a particular firm, risk is not apt to be a negligible factor in the ranking of projects. In effect, the expected value of a project is discounted by the project's uncertainty. As a result, firms will tend to under-allocate resources (relative to the socially optimal allocation) to risky projects; the extent to which this occurs will vary directly with the risk aversity of firms.

Examination of auto industry testimony and history leaves no doubt that the automakers are risk-averse. It is equally clear that the development of alternative powerplants is filled with uncertainty. Uncertainty, therefore, appears to be an important cause for Type II suboptimization in powerplant technology.

There are three sources of uncertainty in powerplant development: the cost of invention, the reaction of consumers, and the reaction of rivals. Discussion of rival reaction is delayed to the next section.

Two estimates of the uncertainty of the costs of invention are available. Ford estimated that the total development costs of the Stirling engine would be between 100 and 200 million dollars.²⁵ Jet Propulsion Laboratory expected that 95 to 130 million dollars were needed to make the gas turbine and Stirling engines practical; however, it

was assumed that even if the projects were funded at those levels, the chance of failure was one in four.²⁶

The second source of uncertainty is the reaction of consumers to a new powerplant. It is possible that the market penetration of a new powerplant will be relatively slow. The average car buyer may be unsure of the merits of an alternative powerplant and may stick with the familiar conventional Otto; fears that a new powerplant will be difficult to service may also discourage sales. On the other hand, the alternative may be perceived by consumers as very superior to the conventional Otto, and this may greatly stimulate car sales.

Similarly, it is uncertain how large a premium consumers will be willing to pay for a car with an alternative powerplant. This is especially important since any alternative would have higher unit production costs than the conventional Otto, not to speak of the sunk expenditures in research and development.

The characteristic on which the profitability of the various alternatives essentially depends is fuel economy. Before the energy crisis the consumer usually paid scant attention to his car's fuel economy: it is not clear to what extent this attitude has changed. Chrysler's uncertainty over the sensitivity of sales to fuel economy improvements is revealed in a 1975 letter from the firm to the EPA:

Accomplishing significant levels of fuel economy improvements should offset to some extent losses due to higher prices. However, quantifying the extent of this offset is difficult for several reasons:

- The lack of any definitive study of this subject either in house, or from outside consultant sources.
- Uncertainty as to the future level of gasoline prices.
- Difficulty in gauging how consumers will respond to relatively modest changes in fuel economy. A 15% change in economy would cost or save the average driver only \$70 per year, even at 75¢ a gallon.

This indication of a very modest impact on operating costs occurring from a 15% change in fuel economy suggests that economy change would have to be considerably above this level before any measurable effect on new car sales could be identified. This point is supported by the fact that we can find no evidence of improved G.M. sales or market penetration this year, despite their strong promotional support for "more efficient" products, with a 10-15% economy improvement. At the same time, it is difficult to prove that declines in economy during recent years resulting from safety and emission standards had any effect on sales.²⁷

Chrysler went on to add, however, that "the greater the degree of improvement" in fuel economy, "the greater the potential impact on sale" and that "strict rationing and/or prices exceeding \$1 per gallon would probably render car sales more sensitive to product economy attributes."²⁸ Certainly all the automakers by the mid-1970's realized that fuel economy was going to be more important than it had been; estimating how much more was another matter.

At any rate, uncertainty appears to be an important factor in the observed allocation of effort in powerplant development. An improved version of the conventional Otto would carry the lowest amount of uncertainty: in comparison

to alternative powerplants, the developmental and unit production costs can be estimated with some confidence; and the reaction of consumers to such an engine is not apt to differ sharply from the many previous times when new conventional Ottos were introduced. All of this is less true for the alternative powerplants. Since the automakers are risk-averse, it is not surprising that the bulk of developmental effort has been focused on improving the conventional Otto.

Similarly, the allocation of effort among the alternatives appears to have been influenced by uncertainty. The electric, Stirling, and gas turbine powerplants carry a much higher degree of uncertainty than the stratified charge, Diesel, and probably, rotary engines. As a result, there has been a tendency to concentrate on the latter group of powerplants, even though the ones in the first group may be superior in the long run.

e. Collusion to Reduce Uncertainty

In Chapter Three it was argued that firms in a concentrated market may collude to reduce the uncertainty associated with innovation. With collusion, the total demand for new technology is less than otherwise would be the case; if so, collusion is a cause of Type II suboptimization. The structure of the postwar auto industry favors such collusion, and events have shown that the possibility of collusion must be seriously considered.

Has collusion slowed down the development of alternative powerplants? Unlike the case of the smog control

devices, there is no evidence that there was or is any overt agreement among major automakers to control the rate of powerplant development.

This leaves the possibility of tacit collusion. The test for tacit collusion is undue parallelism in firms' behavior, i.e., a parallelism which exceeds that which would occur if firms made decisions independently. There is some evidence of such parallelism in the development of alternative powerplants. The story of the rotary engine is the best example.

Felix Wankel, a self-taught German engineer, is credited with the seminal insights which led to the construction of automotive rotary engines. Wankel had been interested in the development of rotary engines since the 1920's, and until the early 1950's much of his work was carried out at his own expense.

In 1953, however, a small German producer of motorcycles, N.S.U. Motorenwerke, began to back Wankel's development of the engine. The contributions of two N.S.U. engineers led to the design of a practical configuration by 1958. This configuration was suitable for automotive use; indeed, N.S.U. was very much interested in this application since it had recently entered the European car market. This period also marked the beginning of the sale of rotary engine licenses to other firms; the royalties from these licenses were shared by N.S.U. and Wankel G.m.b.h., a firm half-owned by Felix Wankel.

In October, 1958 the Curtiss-Wright Corporation bought the North American rights on the rotary from N.S.U./Wankel G.m.b.h. A lengthy period of research and development began, during which rotary engines were designed for boats, lawn mowers, and electrical generation.

Chrysler may have been the first American automaker to experiment with some of the engines from Curtiss-Wright; this occurred in 1962.²⁹ By 1966, each of the Big Three had inspected rotary engines from Curtiss-Wright. These efforts were low-keyed and of an exploratory nature: there was little interest in full development of the rotary engine.

Foreign development of the engine was moving at a quicker pace, however. N.S.U. introduced the first rotary-powered car in 1964. The introduction of Toyo Kogyo's "Cosmo" in 1967 was the first mass production of rotary engines. Other foreign automakers were active in developing pre-production prototypes: Mercedes exhibited a rotary sports car in 1969; also in that year Citroen decided to build 500 rotary-powered test cars; Rolls-Royce, Alfa Romeo, and Porsche had rotary engine programs underway during the late 1960's.

Vigorous development of the engine by the American automakers began in the fall of 1970, when G.M. announced that it had entered into a licensing agreement with Audi-N.S.U., Wankel G.m.b.h., and Curtiss-Wright. The industry product leader stated that it would try to offer cars with

rotary engines by the end of 1973. That the rotary was scheduled for introduction on the firm's subcompact cars indicates that G.M. was attracted by the engine's compactness and its seeming potential for low unit cost of production.

G.M.'s rotary engine project was far from a secret in Detroit. Indeed, in the summer of 1971, Automotive Industries reported the following on G.M.'s decision to push the development of the rotary:

If the decision is to build the RC engine, and the public really takes to it as most RC engine enthusiasts believe they will, then the rest of the industry will be at a decided competitive disadvantage. The future could be disastrous for them for they will be unable to offer RC engines for some time in the future.

G.M. officials must be well aware of this, which may explain why so much information about the RC is being leaked out, much to the consternation of the public relations department at G.M. In effect, G.M. is warning the rest of the automotive industry that a new era is at hand and that they had better get with it.³⁰

G.M.'s fellow automakers took the hint. In January, In January, 1971 it was reported that Ford had begun negotiations with Toyo Kogyo on a possible technological tie-up;³¹ these meetings, however, came to naught. But by November of 1971, Ford had signed an agreement with Audi-N.S.U. and Wankel G.m.b.h. that allowed it to develop the rotary and to manufacture the engine in West Germany.³² Even before this, Ford had begun an intensive program to develop the rotary: by August, 1971 rotary-powered subcompacts were being tested at Ford's research facilities in Dearborn, Michigan.³³

Chrysler was somewhat more reluctant to step up the development of the rotary. Indeed, in August, 1972 Chrysler's vice-president in charge of engineering claimed that the engine was "doomed" as a future automotive powerplant.³⁴

Nevertheless, in October, 1972 Chrysler reported it had started testing rotary engines. Perhaps this change of heart was prompted by an earlier announcement that G.M. planned to offer the rotary on the 1975 Chevrolet Vega. The president of Chrysler still found the rotary to be "an extremely dirty engine but when fifty percent of the auto industry is going to do something about it, we have to."³⁵

Similarly, American Motors announced in October, 1972 that it planned to produce rotary-powered cars. In February, 1973 a licensing agreement between AMC and Curtiss-Wright was revealed.

G.M., Ford, and AMC had intensive rotary programs throughout 1973.

Chrysler, however, ended its program during the first half of 1973.³⁶ Chrysler's decision on the rotary was probably tied to the one not to build subcompact cars in the U.S. During the early 1970's the rotary engine was seen as the likely replacement of the four cylinder conventional Otto; these small Ottos were, and still are, the standard powerplants for subcompact cars. In 1973 Chrysler was the only American automaker not building subcompacts or four cylinder engines although entry into that segment of

the market had been considered since 1969. As the president of Chrysler put it: "The two go together--size of cars and engines."³⁷ The decision not to go ahead with the development of subcompacts would later return to haunt the firm.

At any rate, the great concern about energy at the end of 1973 dampened the prospects for the rotary: relative to the conventional Otto, the rotary's fuel economy left much to be desired. In December, 1973 Eliot Estes (who became president of G.M. in 1974 upon the retirement of the rotary's most important patron at the firm, Edward Cole) . admitted that G.M. had not yet solved cost and fuel economy problems with the rotary engine.³⁸ This meant that G.M. had not yet chosen a final design configuration. Given the usual lead times for engine development, it seemed unlikely that G.M. could introduce rotary powered cars at the beginning of the next model year. Thus it was not surprising that on December 24, 1973 a G.M. spokesman announced that the introduction of the rotary engine Vega would not take place at the beginning of the new model year, as originally planned, but would probably come some time later in the model year. It was added that "all our engine programs are undergoing reevaluation because of the energy situation."³⁹

Ford, no doubt sensing the scaling down of G.M.'s rotary program, ended its program altogether. In March of that year, a Ford representative stated rotary testing had been discontinued "to concentrate funds and manpower on

engines which we believe hold the greatest potential for improving fuel economy and obtaining low emissions."⁴⁰ According to Ford engineers, only a breakthrough by some rival could restart their rotary engine program.⁴¹

In September, 1974 G.M. announced that the introduction of the rotary was being postponed indefinitely; in the next few years G.M. gradually phased out the bulk of its development of the rotary. In early 1975 American Motors dropped its rotary engine plans.⁴² In short, there was little development of the rotary engine on the part of U.S. automakers after 1975.

It is noteworthy that efforts abroad were not as sharply diminished. During 1976 Audi-N.S.U. revealed a new configuration of the rotary with better fuel economy.⁴³ Toyo Kogyo also reported progress with new configurations, including a stratified charge version of the rotary. Toyo Kogyo's manager of rotary engine development insisted that the engine was not dead and that "it's not fair to evaluate the rotary engine on the same basis as the reciprocating engine because it's so young. If it was in the same state of development, it would be different, but we began our development work only in 1961. In a little more than 15 years, where was the reciprocating engine?"⁴⁴ Apparently impressed by these developments, Toyota resumed development of the rotary at the beginning of 1977.⁴⁵ Whether these efforts to improve the rotary are successful remains to be seen.

To sum up the rotary story: during the 1960's, the Big Three carried out low-level, exploratory research on the rotary engine. After commercialization had been made abroad, the product leader decided to develop the engine. The lesser firms followed, perhaps reluctantly, but followed nevertheless, since they did not want to run the risk of being wrong about the engine. Conditions changed with the consequence that increased the uncertainty about the rotary's success. As a result, the product leader began to scale down its program of development; this encouraged the lesser firms to end their development of the engine. After 1975, development of the rotary engine by U.S. automakers was negligible. In contrast, fairly vigorous development of the engine continued abroad.

Such parallelism in the development programs of the U.S. firms strongly suggests tacit collusion to eliminate, or at least lessen, the uncertainty of rivalry in innovation. As a consequence, the total demand for new powerplant technology tends to be less than would be the case under more competitive conditions.

There are other instances of parallelism in the development of alternative powerplants, although these may be somewhat less supportive of the collusion hypothesis. Since the mid-1950's each of the Big Three has experimented with gas turbine engines. With the possible exception of Chrysler during the early 1960's, however, there never seemed to be any serious effort to offer the engine on cars

sold to the public;⁴⁶ it is suspected that prior to the 1970's, these programs were mostly justified by public relations considerations.

The interest of the major automakers in the Rankine engine seemed to have waxed and waned together during the late 1960's and early 1970's;⁴⁷ a similar pattern is observed in the building of "state-of-the-art" electric vehicles. In these cases, however, it is possible the parallelism would have been much the same even if there was no collusion.

To be sure, there have been exceptions to the pattern of parallel development. During the mid-1970's, G.M. and Ford had projects on advanced, high energy batteries while Chrysler did not. A more glaring exception involves the Stirling engine. Although G.M. had experimented with the Stirling during the 1960's, the industry leader had no Stirling program during the 1970's: high unit cost and difficulty in sealing the engine's gaseous working fluid were cited as the chief reasons why work was discontinued.

Ford, however, which apparently had done little or no work with the Stirling before 1971, had a fairly vigorous program of development between 1973 and 1978. Work on the engine was shared with H. V. Phillips. Phillips, a large Dutch manufacturer of electrical equipment and appliances, had been experimenting with the Stirling for more than thirty years. Unlike their counterparts at G.M., engineers at Ford were optimistic about the Stirling: the head of

Ford's powertrain and systems research office, J. D. Collins, stated in October, 1975 that "we have either solved the problems General Motors encountered or have made them inconsequential."⁴⁸

Nevertheless, Ford reduced its efforts to develop the Stirling in 1978 and stated that it needed to "commit a larger share of resources"⁴⁹ to meet short term fuel economy needs; the firm also announced that development of its fuel-injected stratified charge engine, PROCO, was being stepped up. The decision to slow down on the Stirling was made, according to one official at the Department of Energy, despite the fact that the engine "exceeded the company's own anticipation of fuel economy gains."⁵⁰

Thus while Ford work on the Stirling was a temporary exception to parallel development, the firm's priorities in powerplant development are essentially the same as G.M.'s and Chrysler's, viz., relatively certain, conventional approaches receive a higher ranking than projects that are more revolutionary and more risky.

f. Monopsony in the Purchase of New Technology

If the buyers of new technology have market power, they will be able to force the price of new techtils below the competitive level. As a result, the output of new technology will fall short of the optimal rate. A second effect of monopsony power may be at work in the automotive technology market: by tying the purchase of other inputs

to the provision of new technology, the automakers may be able to increase the technology supply of vendors.

The strengths of these offsetting effects are not clear, even in theory. Little guidance is offered by the available evidence on alternative powerplants. Consequently, the extent that Type II suboptimization is due to monopsony is unknown.

g. Final Remarks on Type II Suboptimization

It is hard to gauge the relative importance of the causes of Type II suboptimization. The author's judgment on the matter is as follows.

The difference between the private and social rates of discount and the private aversion towards uncertainty appear to be the most important factors. The inability to practice perfect price discrimination and externalities appear to be relatively unimportant; it is also tempting, merely on intuitive judgment, to put monopsony power in this second category.

Similarly, collusion's role is hard to judge. A cursory cross-sectional analysis may be helpful, however. Consider the European and Japanese firms; these firms have generally operated under more competitive conditions in the global market than the American Big Three have been used to in North America. Consequently, collusion by these firms seems unlikely.

All the innovations of alternative powerplants have come from these firms: the Diesel (Mercedes-Benz), the

divided chamber stratified charge (Honda), and the rotary (N.S.U. and Toyo Kogyo). The absence of any such innovations from U.S. firms, including their European divisions, suggests that uncertainty-collusion is a relatively important cause of Type II suboptimization.

On the other hand, the overwhelming bulk of foreign cars still use the same engine as nearly all American cars, i.e., the conventional Otto. None are powered by any of the more advanced powerplants such as the gas turbine or Stirling. This suggests that the effect of uncertainty-collusion has not been that important.

Therefore, a reasonable guess on the importance of uncertainty-collusion would place it above the price discrimination, externalities, and monopsony factors, but somewhat below the time discount and uncertainty-aversion factors. Additional evidence could easily change this ranking of the causes of Type II suboptimization.

5. Type I Suboptimization in Powerplant Technology

Throughout this chapter it was assumed that the production of powerplant technology was efficient, that is, Type I suboptimization was absent. Whether this assumption was justified is now discussed.

Two possibilities for Type I suboptimization were identified in Chapter Three. The first was organizational slack at the R&D departments of the automakers. While there has been some criticism that the industry's work on alternative powerplant is largely a sham to placate the

public and the government, there is no hard evidence to support the organizational slack hypothesis.⁵¹

The other likely possibility was defensive research that merely duplicated the technology already produced by others. No doubt such duplication went on in powerplant development; with firms working on the same powerplants it would be impossible to avoid at least some duplication of effort. But there is no evidence to suggest that the duplicative waste has been great. This is not surprising when the complexity of powerplant technology is considered: each type of powerplant has an unlimited number of design configurations; consequently there is plenty of room for non-overlapping experimentation.

It does not appear that Type I suboptimization was significant in powerplant development. However, a cautionary note must be added: the kind of information most likely to yield evidence on Type I suboptimization--internal documents and testimony of individuals on the scene--is not readily available to outside researchers.

NOTES

1. U.S. Congress, House, Subcommittee on Energy Research, Development and Demonstration, Committee on Science and Technology, Hearings on Advanced Automotive Research and Development, 94th Cong., 2nd sess., March 1976, p. 508.
2. General Motors Corporation, "General Motors Request for Suspension of 1977 Federal Emissions Standards," Detroit, January 1975, section 4a-7. Hereafter referred to as "G.M.'s Request for Suspension."
3. Ford Motor Company, "Application for Suspension of 1977 Motor Vehicle Exhaust Emission Standards," Dearborn, January 1975, section V. Hereafter referred to as "Ford's Request for Suspension."
4. Chrysler Corporation, "Request for Suspension of the 1977 Federal HC and CO Emissions Standards," Highland Park, January 1975, section IV-G. Hereafter referred to as "Chrysler's Request for Suspension."
5. U.S. Congress, House, Subcommittee on Energy Research Development and Demonstration, Committee on Science and Technology, Hearings on Advanced Automotive Research and Development, op. cit., p. 61.
6. General Motors Corporation, "Automotive Emission Control Expenditures, 1967-1975," information supplied to author.
7. For an idea of the diversity among these technology-producers see the following: U.S. Congress, House, Committee on Science and Technology, Inventory of Energy Research and Development: 1973-1975, Committee Print, 94th Cong., 2nd sess., Jan. 1976, Vol. II, pp. 1982-2034; U.S. Congress, House, Committee on Science and Technology, Inventory of Advanced Energy Technologies and Energy Conservation Research and Development, 1976-1978, Committee Print, 96th Cong., 1st sess., Jan. 1979, Vol. III, pp. 2312-2383; U.S. Congress, Senate, Committee on Commerce, Hearings on Automotive Research and Development and Fuel Economy, 93rd Cong., 1st sess., May 1973.
8. U.S. Congress, House, Committee on Science and Technology, Inventory of Advanced Energy Technologies and Energy Conservation Research and Development: 1976-1978, op. cit., pp. 2317-2383.

9. Ibid., U.S. Congress, House, Committee on Science and Technology, Inventory of Energy Research and Development: 1973-1975, op. cit.
10. Letter to author from Paul V. Lombardi, Automotive Technology Development Division, Department of Energy, July 25, 1979.
11. U.S. Federal Energy Administration, The Role of the Federal Government in Automotive Research and Development (Washington: U.S. Government Printing Office, 1974), p. i.
12. Ibid., p. ii.
13. Massachusetts Institute of Technology, Energy Laboratory, "The Role for Federal R&D on Alternative Automotive Power Systems," Cambridge, MA, November 1974, p. iv.
14. Massachusetts Institute of Technology, Energy Laboratory, "Federal Support for the Development of Alternative Automotive Power Systems," Cambridge, MA, March 1976.
15. Ibid., pp. x-xi.
16. Ibid., pp. xviii-xix.
17. Ibid., p. xvi.
18. Jet Propulsion Laboratory, Should We Have a New Engine? (Pasadena: California Institute of Technology, 1975), vol. 1, p. 10.
19. Ibid.,
20. U.S. Congress, Senate, Committee on Commerce, Hearings on Automobile Fuel Economy and Research and Development, 94th Cong., 1st sess., March 1975, p. 144.
21. Ibid., p. 164.
22. U.S. Congress, House, Committee on Science and Astronautics, Subcommittee on Space Science and Applications, Hearings on Research on Ground Propulsion Systems, 93rd Cong., 2nd sess., January 1974, pp. 249-250.
23. Minutes of Advisory Committee on Advanced Automotive Power Systems meeting, February 13-14, 1975, pp. 7-8, emphasis added.
24. Economic Report of the President, 1978, p. 92.

25. Massachusetts Institute of Technology, "Federal Support for the Development of Alternative Automotive Power Systems," op. cit., p. 203.
26. Jet Propulsion Laboratory, op. cit., vol. 2, p. 12-18.
27. Letter from S. L. Terry, Vice President of Public Responsibility and Consumer Affairs, Chrysler Corporation, Feb. 17, 1975.
28. Ibid. The "targeted 40% improvement" refers to the proposal of President Ford that the auto firms pledge to increase the fuel economy of their cars by that amount by 1980.
29. Wallys Wys, "The Engine Detroit Couldn't Ignore," Motors Trend, 24 (November 1972): 62-64.
30. James P. Pond, "Second Thoughts on RC Engines," Automotive Industries 145 (Sept. 15, 1971): 23.
31. No doubt Ford was well aware of G.M.'s interest in the rotary by at least mid-1970. See D. N. Williams, "Is G. M. Trying to Wangle the Wankel," Iron Age 205 (June 11, 1970: 31; "Widening World of Wankel," Machine Design 42 (July 9, 1970): 50.
32. Wall Street Journal, November 30, 1971, p. 8.
33. "Wankel Engine in U.S. Cars Certain in About Two Years," Automotive Industries 145 (August 15, 1971): 17.
34. Automotive Industries 147 (August 1, 1972): 19.
35. Washington Star, November 17, 1972, p. 1.
36. "Sign of the Times," Forbes 113 (March 15, 1974): 27.
37. Wall Street Journal, February 9, 1973, p. 19.
38. Automotive Industries 149 (December 15, 1973): 19.
39. New York Times, December 25, 1973, p. 28.
40. Wall Street Journal, March 11, 1974, p. 3.
41. Ibid., May 21, 1974, p. 1.
42. U.S. Environmental Protection Agency, "Automobile Emission Control," Washington, April 1976, p. 7-8.
43. "Audi-NSU to Test Improved Wankel," Automotive News, January 13, 1977, p. 1.

44. "Rotary Not Dead, Developer Says," Automotive News, January 10, 1977, p. 23.
45. "Toyota to Resume Efforts to Develop Rotary Engine," Automotive News, January 31, 1977, p. 130.
46. See the following on the Big Three's earlier experiences with the gas turbine: Chrysler Corporation, "History of Chrysler Corporation Gas Turbine Vehicles," Highland Park, 1974; R. D. Roddant, "End of the Road for Piston Engine," Iron Age 173 (April 15, 1954): 82; F. G. Lawrence, "Gas Turbine Pace Quickens," Steel 137 (December 5, 1955): 95-96; "Ford Tries Out Two New Turbine," Business Week, March 16, 1957, p. 132; "Turbine Car for Masses?", Business Week, January 6, 1962, pp. 36-7; "Turbine Car Awaits Chrysler Decision on Mass Production," Iron Age 197 (April 21, 1966): 13.
47. U. S. Congress, Senate, Committee on Commerce, Hearings on Automotive Research and Development and Fuel Economy, op. cit., p. 310; "Ford's Request for Suspension," sec. V-c, p. 16; "Chrysler's Request for Suspension," sec. IV-G, pp. 18-19.
48. "Ford Notes Progress With Stirling," Automotive News, October 6, 1975, p. 6.
49. Wall Street Journal, October 15, 1978, p. 15.
50. Ibid.
51. See, for example, U.S. Congress, Senate, Committee on Commerce, Hearings on Automotive Research and Development, op. cit., pp. 17, 94.

CHAPTER V

CONCLUSIONS

1. Auto Industry Progressiveness

Progress in the most important area of automotive technology has been deficient. This thesis has examined the technological opportunities in automotive powerplants and has found them to be abundant. But it has also found that the exploitation of these opportunities was well below the socially optimal level. In short, the market system failed to allocate enough resources to the invention of better powerplants.

This market failure involved a number of factors, which can be put into three groups of varying importance. Differences between the private and social time discount rates and between the private and social aversities towards uncertainty appear to be the two most important factors. Collusion to reduce uncertainty appears

somewhat less important. The factors that appear to contribute least to the market failure were monopsony in the purchase of new technology, externalities in innovation, and the inability of firms to impose perfect price discrimination upon the consumers. However, the evidence gave little firm guidance in establishing these rankings: they are based largely on intuitive judgment and, as a result, must be accepted with caution.

It is unclear whether a better powerplant than the one being produced was already available during the mid-1970's. In comparison to the conventional Otto, every alternative powerplant had at least one disadvantage. On the other hand, no alternative was inferior to the conventional Otto in every way. Even so, some evidence suggests that the American industry was too slow in offering Diesel engines to the public. However, this delay may have been justified by uncertainty over federal standards for NOx emissions.

Finally, little can be said about the efficiency of the invention process itself. Structural conditions suggest that technology production by vendors and investor-firms is efficient while that of the automaker's R&D departments may not be. However, there is no hard evidence to support these inferences.

2. Market Structure and Progressiveness

a. Firm Size

Although invention offers future benefits, it consumes resources today. Sales revenue is the likely source of these resources for the firm. The larger the revenues, the greater the ability of the firm to support R&D. Moreover, indivisibilities in the production of new technology (i.e., progress comes in chunks of techtils called innovations) raises the possibility that a certain minimum size is required for effective invention. While there are many variants, this line of reasoning underlies the common hypothesis of a positive relation between firm size and invention.

This hypothesis, though not completely wrong, is overly simplistic, when applied to the automotive field. This is true because it ignores two critical facts about the invention process. First, progress has been usually made in small steps; in other words, sizable indivisibilities in the production of technology are not common. Consequently there is plenty of opportunity for small firms to make valuable contributions to progress.

The second critical fact about the invention process (which in a way is related to the first) is its sequential nature. Although the various stages of research and development share the goal of producing new knowledge, they differ fundamentally in the resources they require.

At the earlier stages, the crucial input is creative insight; relatively small amounts of tangible resources are apt to be needed. Such modest requirements are within the reach of fairly small firms or even individual inventors such as Rudolph Diesel or Felix Wankel. At later stages of the invention process, the opposite is true. The final development of a new auto engine is expensive work. Nevertheless, giantism is not essential: it is noteworthy that the three alternative powerplants on the market today (the Diesel, the rotary, and the divided chamber stratified charge) were developed by relatively tiny automakers.

In short, while size may limit the firm to certain stages of the invention process, there is no unique size for effective invention. The diversity in the size of automotive technology producers supports this conclusion.

Another conclusion of this thesis is that research intensity figures--R&D expenditures as a percent of sales--may be misleading indicators of progressiveness due to inter-firm differences in vertical integration. Data for the four American automakers showed a roughly positive relation between research intensity and firm size. When value added was substituted for sales, however, no clear relation between research intensity and size was evident. The explanation for this is that the smaller and less integrated firms buy more technology from vendors than their larger rivals who, on the other hand, rely more heavily on in-house research and development.

b. Market Concentration

There are two basic hypotheses on concentration and progressiveness. One states that concentration promotes invention and innovation. Profits are apt to be relatively high in a concentrated market. Consequently, it is argued, the ability of firms to finance invention is strong; moreover, the prospect of high profits after innovation makes firms more willing to invent and innovate. The alternative hypothesis is that concentration discourages invention and innovation. Under this hypothesis, competition is the driving force of progress. The desire to stay alive, it is said, is a stronger incentive than monopoly profits; extraordinary financial ability is said to be unnecessary for effective invention and innovation.

In short, the concentration controversy involves two factors: ability and willingness. Ability varies directly with profits. But profits and size tend to vary directly too, and, in the post-war auto industry, the rate of profit has also generally varied with firm size. Thus, as far as ability is concerned, the effects of firm size and concentration are indistinguishable and inseparable.

The conclusions on concentration, therefore, follow from those on firm size. While modest concentration in automaking--something on the order of a four firm concentration of fifty percent--is desirable due to the high cost of final development in automotive innovation, the high current level of concentration does not seem to have

unique advantages for industry progressiveness. To be sure, an automaker with only twelve percent of the market could not support an R&D network like G.M.'s. However, it is unlikely that invention would be impaired as a result. Instead, firms would rely more heavily on vendors and other technology producers. Furthermore, joint ventures among firms would offer an attractive solution to the problem of unusually large indivisibilities in the production of new technology.

Nor has the high level of concentration made automakers especially eager to invent and innovate. Certainly it has given discretion to managers, especially those at G.M. Although its discretionary power has been somewhat reduced by foreign firms, G.M. is still the product leader of the U.S. industry. Consequently the progressiveness of the U.S. industry is largely determined by managerial decisions at G.M. Since G.M. has been generally conservative in its product policies, it is hard to see how this arrangement has encouraged progressiveness.

To be sure, it is conceivable that radical-thinking managers may gain control; indeed, past changes in corporate management have resulted in noticeable changes in product policy. Here, the effect of managerial decision-making in oligopoly is to give progressiveness a theoretical indeterminateness similar to that of price.

3. Implications for Public Policy

The demand for new powerplant technology should be increased. There are a number of ways to do this.

a. Energy Prices

The price of energy should be completely decontrolled to reflect the growing scarcity of the resource; taxes on energy may also be justified. Such action would increase the profit potential of alternative powerplants with better fuel economy and, as a result, would increase the demand for the technology needed to make them practical.

b. Government-induced Demand

Government contracts should be offered to solve the key problems that are now holding up commercialization of better powerplants. For the most part, government-supported work should concentrate in basic research, the area most neglected by the private sector. Nevertheless, while needless duplication of private effort should be avoided, competition with private technology production should not be ruled out. The automakers should not be allowed to assume that if they drop support of a project the work will still get done with public monies. Moreover, the threat of government-induced competition may stimulate the private demand for new technology.

c. Government Entry into Automobile Production

While government support of technology production would reduce Type II suboptimization, the possibility of Type III suboptimization--the neglect of valuable new technology--remains. One way to prevent Type III suboptimization would be to set up a government-controlled enterprise to test new concepts in the marketplace. In addition to providing information about profitable opportunities, this enterprise would serve as a yardstick to measure the performance of private automakers.

This is a radical proposal and should be pursued only if there is a strong presumption of Type III suboptimization. This thesis provided little evidence in support of such a presumption. Moreover, future neglect of advanced powerplant technology by domestic automakers may be unlikely if foreign firms continue (or are allowed to continue) their innovative and aggressive assault on the U.S. market.

d. Current Public Policy

For the most part, current public policy is in line with the recommendations of this thesis. There has been movement to decontrol energy prices. More important federal efforts to increase the demand for powerplant technology increased sharply after 1975.

The present controlling legislation is the Advanced Automotive Propulsion Research and Development Act of 1978. Noting "insufficient resources are being devoted to both

research on and development of advanced automobile propulsion system technology," Congress instructed the Secretary of Energy to:

. . . make contracts and grants with any Federal Agency, laboratory, university, nonprofit organization, industrial organization, public or private agency, institution, organization, corporation, partnership, or individual for research and development leading to advanced automobile propulsion systems which are likely to meet the Nation's long-term goals with respect to fuel economy, environmental protection, and other objectives.¹

Patents that result from federally supported work go to the government. The Secretary of Energy, however, has been given the power to waive patent rights to an inventor if the public interest is served.²

The possibility of Type III suboptimization was recognized by Congress. It told the Secretary of Transportation to study annually "the extent to which the automobile industry utilizes advanced automotive technology" and to make "appropriate recommendations which may encourage the utilization of advanced automobile technology by the automobile industry."³

A regrettable provision of the law prohibits any duplication of private efforts: private efforts are to be merely supplemented. As a result, the automakers may be able to shift to the public expense work that they otherwise would have supported; also, the provision precludes government supported work from acting as a competitive stimulus.

4. Recommendations for Further Research

a. Automobile Industry

Further investigation is needed in two areas. First, more information is needed on the structure of the automotive technology market. It would be good to know more about the number, size, and motives of technology producers. Barriers to entry and the effects of monopsony power also need more study. Possibly such structural knowledge may have valuable public policy implications: for instance, the output of new technology may be more effectively increased by policy directed towards supply rather than demand.

The second area that needs further investigation is Type I suboptimization. Theoretical treatment of defensive research requires more thought. More empirical evidence is certainly needed. Interviews with engineers and managers at technology producers would contribute much. Internal corporate documents would be even better, but they are likely to be beyond the reach of the private investigator.

b. Application of This Thesis' Methodology to Other Industries

This thesis differed from many of the past studies of technology change in two ways. First, it was an industry study instead of a cross-sectional analysis of a number of industries. The major advantage of the industry

approach is that it avoids the difficulty of controlling for inter-industry differences in technological opportunities. The industry study approach, however, has a serious drawback: it is difficult to rank the causes of non-optimal performance. To determine the causes that are most important, some sort of cross-sectional analysis must be used.

The second way this thesis differed from past studies is that it stressed performance and not conduct. While conduct studies are interesting, the studies of performance are apt to be more valuable. The first step in an enlightened public policy is asking whether remedies are needed at all. Consequently, knowledge of industrial performance is essential.

Therefore, application of this thesis' methodology to other industries promises benefits in two areas. First, by comparing industries, the factors that generally promote or retard progress may be more clearly revealed. Second, the discovery of poor industrial performance may lead to remedies that will strengthen the economy.

The recommended methodology is tedious and time-consuming. As a result, the selection of industries for future investigation must be carefully thought out; the industries named in the Hart Bill are certainly worthy candidates.⁴ But whatever industry is chosen, the recommended methodology is as follows. Analyze the institutional setting for technological change in the industry.

Identify the forces that determine the rate of progress. Next, evaluate the current state of technology and the available technological opportunities. Finally, study whether firms have adopted the best technology already available and whether they are making a satisfactory effort to exploit the available opportunities.

NOTES

1. 15 U.S.C., sections 2701, 2702.
2. 42 U.S.C., sec. 4908.
3. 15 U.S.C., sec. 2704.
4. The Industrial Reorganization Act, often referred to as Hart Bill in honor of its chief sponsor, the late Senator Philip Hart, proposed in-depth studies of the following industries: chemicals and drugs, electrical machinery and equipment, electronic computing and communications equipment, energy, iron and steel, motor vehicles, and nonferrous metals.

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