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**FEDERAL SUPPORT FOR THE DEVELOPMENT OF ALTERNATIVE
AUTOMOTIVE POWER SYSTEMS**

**The General Issue and the
Stirling, Diesel, and Electric Cases**

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**FEDERAL SUPPORT FOR THE DEVELOPMENT OF ALTERNATIVE
AUTOMOTIVE POWER SYSTEMS**

**The General Issue and the
Stirling, Diesel, and Electric Cases**

**Working Paper Submitted to
The Office of Energy R & D Policy
National Science Foundation**

by

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SUMMARY AND CONCLUSIONS

Introduction - Over the last decade or so the question of the place of alternative automotive powerplants in the future of the American passenger car has been a controversial one. The air pollution and energy problems have become social issues in which changes in automotive engine technology must inevitably play an important role. However, the industry's alternative powerplant R & D programs have been small compared to its massive investments in R & D and in plant and equipment for modifying the internal combustion engine (ICE), the associated driveline, and the bodies and frames of their new vehicles. The apparent reluctance of the industry's "Big Three" to deal "seriously" with the alternative powerplants has led to calls for massive Federally-supported R & D programs designed to produce "production prototypes" on a crash basis, much as the Apollo program accomplished a national goal through such R & D. The industry position has traditionally been that they provide what the automobile customer wants; that the future of automotive technology should be determined by those who know it best, i.e., itself; and that any government funding in the area would therefore be invested in technologies either already being given suitable consideration in industry or whose expected outcome would not justify the expenditure.

This is the issue we have examined. Put succinctly: Should the Federal Government support the development of alternative automotive powerplants? We specifically address programs whose purpose it is to advance the technology with the ultimate goal that the new power systems would be incorporated into substantial numbers of new passenger cars. We have

approached this issue by assuming that the Big Three behave in a manner which reflects their and their managements' self-interests, which are in various ways different from the interests of society as a whole, and that government interventions in the automobile market should be aimed at attaining a more socially optimal behavior of the automotive sector. This would be accomplished by arranging a better alignment of the Big Three's self-interests with those of society, by influencing other firms in the automotive market, or through direct government activity. We have specifically examined how the government might perform this function by supporting R & D on alternative powerplants. Three specific technologies are analyzed in detail as representative of the three general classes of alternative power systems: the Stirling engine, from among the advanced heat engines; the diesel engine, from among those engines not too dissimilar from the ICE; and the electric vehicle, which would have operating features and societal impacts substantially different from those of any of the heat engines.

R & D support is the only government policy tool we explicitly examine; we take the view of the R & D planner by assuming that other government interventions in this market, such as changes in the Clean Air Act or fuel economy improvement programs, are uncertain over the time-frame of interest -- the 1980's and 1990's -- and independent of alternative powerplant developments. This assumption is realistic because the performance standards actually implemented in such regulatory programs must be tied to the "available technology", and, due to the time scales involved in major technological changes, the "available" powerplant technology is and will

continue to be the ICE over this timeframe. These regulatory programs therefore have been, and will likely to continue to be, conducted independently of alternative powerplant developments. We do address the impacts these programs have on alternative powerplant development.

The Process of Automotive TD&P - Our analysis begins with a brief examination of the present market for passenger cars, including the supply side (principally the Big Three -- General Motors, Ford and Chrysler), the demand side, and the present government interventions. We are interested in how major technological changes, such as the development and introduction of a new powerplant, have been handled in the past and how they are likely to be handled in the future. A simple descriptive model for this process of "technology development and production" (TD&P) is developed; the model consists of sequential stages of development or productive activity, and intervening decisions to advance, continue or terminate an evolving system among the stages.

Several conclusions emerge from this examination of the present market. First, the barriers to entry in the automotive industry, and the Big Three's demonstrated willingness and ability to respond to technological threats from other automobile manufacturing firms, imply that they will continue to control the domestic market. It follows that they do make major technological product changes when external technological threats must be averted, and also, though less certainly, when significant technological opportunities arise. Second, major technological change in this industry is very risky business. This is due in part to the replacement nature of the demand for automobiles; i.e., that most new cars are sold as replacements for old ones and therefore the decision to buy a new car is one that

usually can be easily postponed. In part it is also due to the high level of performance and cost optimization achieved in the continuous evolution of the automobile, whose principal subsystems are mostly improved versions of those used continuously for nearly half a century. These features result in a demand for automobiles which is highly variable and unpredictable, both over time and in its response to various technological attributes, and a manufacturing process which is highly capital intensive and thus relatively inflexible. Any major technological change must therefore be preceded by a lengthy and expensive R & D process, and major investments in plant and automated mass production equipment, before being introduced into the marketplace; thus the risky nature of major innovations. Third, there are steps the manufacturers can take to reduce the possible dollar loss associated with the failure of a major technological product innovation, principally associated with the failure of a major technological product innovation, principally associated with designing the innovation for a high degree of "integrability". This and other measures taken to hold down the total initial investment in the innovation, both in the Big Three and in associated support industries (especially fuel supply), provide an "introduction barrier", which an innovation must overcome before its advantages can be fully realized by consumers. Fourth, the history of government involvement in the automobile industry has further added to the uncertainties involved in major changes, as perceived by the industry. Finally, the necessarily lengthy stages of TD&P, plus the subsequent turnover of the in-use fleet, mean that on the order of fifteen to twenty years would elapse from commencement of an intensive R & D program on a major technological innovation until the resulting significant change in the average attributes of the nation's automobile fleet.

The Federal R & D Decision - Our analysis of the Federal R & D decision begins by sorting out the various reasons why the government might want to do R & D on alternative automotive powerplants. R & D for the objective of advancing the state-of-the-art should be justified, as discussed above, by some divergence between the self-interest of the Big Three and the nation at large. Such a disparity can be reasonably well demonstrated in this case, due principally to: (1) generally recognized features of the economics of R & D investment which apply to all technologies, but which are uniquely significant in this industry due to the vast economic impact of the production and operation of its product, (2) the disparity between the value of automotive fuels and their market price, caused principally by a national goal for security from dependence on foreign supplies not reflected in the market price and government price controls which hold the market price of automotive fuel well below its value to the nation, and (3) the Clean Air Act, which forces the industry to focus its R & D resources on technology available in the very near-term, thus reinforcing its natural predilection toward small and evolutionary changes, and which adds risk to long-term investments due to uncertainties in the standards of the regulated air pollutants, the possibility and unpredictable level of standards for presently unregulated air pollutants, and possible government responses to the availability of new technology. While this social-private disparity means that the government should be "sympathetic" toward proposals for government support of alternative powerplant R & D, it provides little in the way of guidance for project selection or program design.

A crucial feature of government-supported automotive R & D is that it is attempting to influence the technology of a consumer product; this is in notable contrast to most previous government-supported technology development for which the Federal Government itself was the purchaser. Thus any technology supported by the government must be ultimately "commercialized", i.e., it must meet the test of the marketplace (including whatever government interventions are extant at that time). Two implications of the commercialization requirement are of great importance. First, any government-supported technology must not only be socially beneficial (in order to merit government support) but it must be privately advantageous as well (or it will fail the market test). Given the important discrepancies between the social and private interests in the automotive market as cited above, this implies important limits on the ability of government support of R & D alone to correct social-private disparities. Second, it implies that Big Three involvement in automotive R & D is very important during the last stages of R & D because (i) only the Big Three have the experience and capability to perform the key element of final development; i.e. initial cost reduction through product design and process development; similar considerations apply to other key elements such as "integrability" and "pleasability", and (ii) Big Three involvement, through financial contribution, is desirable because it insures that industry's evaluation is that the ultimate product may well be marketable, and provides the necessary incentives for incorporating and emphasizing the key market features which could be the crucial determinant of the system's success.

A number of important features of the government's automotive R & D decision severely limit the applicability of quantitative evaluation techniques to project selection. First, the choice is dominated by massive uncertainties which make the net benefits of the interesting alternative powerplants uncertain over a range at least equal to their most likely level. These uncertainties include: the future price of fuel, future consumer tastes, future emissions standards, and the extent of the technological evolution of the ICE. Second, it is not clear how to evaluate what industry might do toward supporting alternative powerplant R & D in the absence of Federal support. Third, some of the relevant national objectives are unclear, such as the nation's willingness to pay for reduced petroleum imports or reduced air pollutant emissions. Finally, small improvements in automotive technology, such as a several-percent savings in fuel consumption costs, result in massive future benefits, with a present value easily in the billions of dollars; making many projects with even very low probabilities of success apparently beneficial on the net.

In the face of these considerations what can be said about a rational role for the government in supporting alternative automotive powerplant R & D? First, the goal for such programs should be reduced social life-cycle cost of automobile operation, while meeting long-term emissions standards, and treating other non-pecuniary attributes on a case-by-case basis. An important feature of such a goal is that it explicitly treats the value of "energy conservation" by incorporating an appropriate social value of automotive fuel.

Second, individual projects should be evaluated by a crude cost-benefit analysis, which would include: an examination of the state of the technology, present programs and the key technological or other barriers which explain the level of industry interest; an evaluation of target attribute levels and the probability of meeting them (or the incremental probability associated with government expenditures if an industry program is already underway); an evaluation of the likelihood of commercialization; and, finally, estimates of the usual social costs and benefits. The relative emphasis among these analyses will be quite idiosyncratic to the particular technology in question.

Finally, the design of government programs must be carefully tailored to the particular technology, its status in industry, and the reasons for that status, at any given time. These provide the government with a guide as to where its R & D efforts must be focused. Given the great uncertainties involved, it is clear that any government program must be carefully reevaluated on a periodic basis -- in both social and private terms. The R & D program itself will reduce the technological uncertainties; whether or not the remaining uncertainties, such as emissions regulations, will be resolved with time is unclear. However, it is clear that any government program must be carefully aligned with the industry process of TD&P; most importantly it would be desirable to have direct cost-sharing programs in the final stages of R & D (as discussed above). While it will be impossible to tell just what level of R & D investment the industry would undertake in any given instance without government support, the features of the automobile market which would tend to cause the industry to underinvest in alternative powerplants R & D (discussed above) make it likely that a "toughly" negotiated cost-sharing agreement would be somewhere close to equitable.

The Baseline ICE - One of the critical uncertainties in evaluating the potential benefits of the alternative powerplants is the extent to which the baseline technology will change. The key attributes of the ICE, its fuel consumption and cost, are therefore evaluated as a function of time and the emission standards imposed upon it. That is, we have projected the likely progress of the extensive industry programs in this area. With no change in emission standards, the minimum expected engine economy improvement by 1985 is about 15%, relative to the 1975 engine; gains much larger are possible. The imposition of more stringent emissions standards could result in losses of up to about 25%, relative to the 1985 engine at present standards. The principal uncertainty is that associated with the change due to emission standards, and it adds substantially to the uncertainty in the benefits of any alternative powerplant. The 1985 ICE could cost up to about \$150 more than the present ICE, due both to efficiency and emissions improvements, but this is probably smaller than the impact of efficiency changes on vehicle life-cycle costs.

The Stirling Engine - A case study on potential government support of R & D on the Stirling engine illustrates virtually every feature of the general problem as described above. The Stirling engine is representative of a major class of alternative powerplants. These are advanced heat engines which are substantially different from the ICE, offer low emissions, relative insensitivity to fuel properties and, possibly, high vehicle fuel economy; but would require a major development effort before their actual attributes and economic competitiveness with the ICE can be determined. The modern automotive Rankine cycle and gas turbine engines are the other important (although distinctive) members of the class.

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 principal uncertainty is the engine's initial cost, which will likely lie in a range from the cost of the present ICE to about twice that. Maintenance costs are also uncertain. At the present time 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 net benefits. A simple total operating cost model developed for Stirling-powered vehicles illustrates the impact of the critical uncertainties on the key development target -- the engine's initial cost -- and the potential benefits which might be obtained from its commercialization. At the engine costs in the range of interest, the uncertainty in the system's total social operating advantage is as large as its likely level -- several tenths of a cent per mile. Similarly the maximum allowable premium of engine cost over the ICE (for positive total operating benefits), is uncertain over a range as large as its likely level -- up to 50% or so. However, 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 investment on

the order of \$100 to 200 million, over 5 to 10 years, is likely to be a very good gamble.

The ways in which the government might involve itself in advancing the Stirling system in the process of automotive TD&P deserve close analysis. No major introduction barriers are likely for the Stirling system except that many early Stirling users would probably run their vehicles on gasoline, at a sacrifice in potential operating benefits. Some early owners might be able to use diesel fuel, but the emissions issue on such heavier fuels remains open. The criteria used by industry in their decision to introduce the Stirling system would focus on initial system cost (although of course many other criteria are involved); an analysis of the social-private disparities previously discussed indicates clearly how a socially beneficial system might be too expensive to be considered privately advantageous. The implications for government-supported R & D are unfortunately clear: unless the government intervenes to further change the marketplace incentives, technologically-successful government-supported development of a socially-beneficial Stirling engine may well terminate without commercialization.

Because the Stirling engine is in the stage of R & D where initial cost is the crucial attribute under development, the R & D activity should be centered in the automotive industry. A cost-sharing agreement with one of the Big Three would be most desirable, because a financial commitment by one of them would give it a stake in a positive outcome, an outcome which they are in fact best equipped and motivated to produce.

The Ford Motor Company is presently involved in completing the initial development of a Stirling engine, including vehicle testing of an early demonstration engine, jointly with N.V. Philips of Holland. Ford plans to request that the U.S. Government enter into a cost-sharing agreement with it for the completion of the development program. As discussed above, this is the type of program which the government should seek in this area. Crucial issues will be the total program level and how the costs should be split. Control of the patents for newly developed technology would be of lesser importance in this case since the system is in the late stages of development. It is difficult for us to offer specific guidance on these questions; obviously a complicated negotiation procedure would be involved. All we can say is that the government should be "sympathetic" but "tough". Crucial technical judgments will have to be made on the significance of various individual subprojects and their importance to the project's overall success. However, we support the concept of the shared-cost program with Ford on the Stirling engine, with both the government and Ford bearing a substantial fraction of the \$100-200 million likely to be involved. As discussed above, such a program is probably a very good gamble for the U.S. Government to take.

The Diesel Engine - In contrast to the Stirling engine, the diesel is a relatively well developed technology which has been used for automotive propulsion, including passenger cars, for many years. It is representative of a class of alternative powerplants which are heat engines not too dissimilar from the ICE. Other engines in the same class are the Wankel

spark-ignition engine and the various types of stratified charge engine. They are all in production for the passenger car application (though not in the United States), and would allow the use of manufacturing technologies and equipment very similar to those in use today. The diesel and some stratified charge engines potentially offer a vehicle fuel economy advantage over the ICE, but little or no advantage in air pollutant emissions.

Lightweight, high-speed diesel engines have been designed for and produced in the European and Japanese automotive markets for many years. The diesel is also used in high mileage taxis and urban delivery vans in these markets. A small number of European-made diesel-powered passenger cars are imported onto the United States. In larger engine sizes, the diesel is produced by several American manufacturers and extensively used in buses and heavy trucks.

At a given power level, the diesel is considerably heavier, bulkier and more expensive than the ICE. Its emissions of hydrocarbons and carbon monoxide are inherently low and do not require the initial and operating expenses for their reduction to the statutory levels that would be required of the ICE; but its emission of oxides of nitrogen cannot be reduced to the present statutory levels (0.4 g/mile) with known or foreseeable technology, in contrast to the ICE. It also emits larger quantities of currently unregulated pollutants -- especially particulates, sulfur oxides, and odor. The diesel engine is inherently much more efficient than the ICE, but the extent to which this is translated into a higher vehicle fuel economy depends strongly on the acceleration to which the diesel-powered vehicle is designed, as does the initial cost premium

for the diesel vehicle. The diesel could use a less expensive fuel than the ICE (at least initially), and has lower maintenance costs, and generally matches the ICE on most other attributes. Turbocharging may affect the weight penalty, but this is presently unclear. Some advanced concepts are under consideration, but, other than the potential use of ceramics, they do not appear to offer major changes in the attributes of the diesel relative to the ICE.

A number of factors significantly influence the desirability, and the likelihood, of the introduction of a domestically-produced diesel vehicle. The economics of the diesel vehicle relative to the baseline ICE depend strongly on its relative acceleration. If the engine is designed with a displacement equal to that of the ICE it would replace in a vehicle, as would likely be the case when it is first introduced, the diesel vehicle's acceleration would be significantly poorer. The engine's initial cost would be 10 to 50% higher than the ICE's, but this would almost surely be more than balanced by decreased maintenance and fuel costs (including a 3-4¢/gal fuel price advantage corrected for equal energy content, and at least a 30% relative fuel economy improvement). At higher levels of performance, the fuel economy advantage is less, the initial cost penalty is greater, and it is unclear whether the total operating economics are advantageous. Because of the lower specific power of the diesel, the total "cost" of vehicle performance is much greater for the diesel than the ICE, so that even in the long run (after any introduction barriers are overcome), diesel vehicles will generally be designed for lower acceleration. While these technological uncertainties are not unimportant, they can be, and are being, resolved by the industry at modest

cost. This situation must be contrasted with the case of the advanced heat engines such as Stirling.

Of greater importance, since their resolution is much more difficult and in fact unlikely, are the other uncertainties. First, there is the emissions issue. In contrast to the Stirling case, the schedule of future emissions standards has a direct impact on the economics of the diesel and whether it can even be legally sold in passenger cars, as well as indirect impacts due to its effect on the ICE. The most prominent uncertainty is in the date when (if ever) the NO_x standard will be reduced below the effective limit for diesel technology; at present this occurs in model year 1978. Adding significantly to this uncertainty are questions associated with the diesel's unregulated air pollutant emissions, which would presumably become regulated should the engine be marketed in significant quantities. Another important uncertainty is the market appeal of the diesel vehicle which would likely be introduced. To minimize the capital investment at introduction, it would likely have an engine with a displacement roughly equal to the ICE it replaces, have a higher initial cost but substantially lower operating costs, and be significantly poorer in acceleration. Finally, fuel cost (in the long run) is unclear, as the widespread use of the diesel in passenger cars would require changes in petroleum refinery output mix, and the cost advantage of diesel fuel over gasoline would likely diminish.

Based on these considerations the government's role in advancing diesel technology can be addressed. Because the diesel is a relatively mature

technology, for which development incentives have long existed, it is unlikely that Federal support of R & D on the diesel would significantly change its attributes over the next five to ten years. The principal issues presently inhibiting diesel engine development and production for passenger cars center on areas other than uncertainty in diesel technology. First, there is the issue of consumer acceptance of the set of attributes the diesel provides. As with the Stirling, this is affected by the government fuel pricing policies. For the most part, however, it is the type of uncertainty which the industry is used to handling. Second, and of a different nature, is the emissions issue, which is controlled by the government. There does not now exist a solid basis for any schedule of NO_x emissions standards. This is of course vitally important to the ICE as well. The effort required to bring a higher level of rationality to emissions regulation is modest compared to the costs of a standard which is unjustifiably high or low, but there is little government effort presently in this area; nor has there been since it was widely recognized over five years ago. The situation with respect to the presently unregulated pollutants is similar in that the uncertainties themselves are very expensive to the nation over the long run, due to their inhibition of technological innovation, as with the diesel.

Thus, we conclude it is unlikely that there are significant gains to be realized through government support of diesel engine technology development for passenger car application. But government research programs designed to place light-duty vehicle NO_x emission standards on a

sounder basis, and examine thoroughly the potential impact of diesel particulate, sulfate, odor (and other unregulated) emissions if diesels were introduced in large numbers, would contribute significantly to the industry's ability to assess the attractiveness of the diesel relative to the ICE. Uncertainties in these areas currently inhibit diesel engine development and introduction.

The Electric Vehicle - The electric vehicle raises a substantially different set of issues than the heat engines. Widespread use of electric vehicles would make major changes in the character (rather than just the degree) of the environment impact and energy consumption of the passenger car fleet. Furthermore, the vehicle itself would be significantly different from heat-engine-powered vehicles on a highly valued attribute -- its range (between battery charges). The range of electric vehicles is inherently limited and depends significantly on factors not generally considered by present vehicle drivers when planning trips. Because the electric vehicle is likely to become the passenger car technology which is generally preferred only in the (hopefully avoidable) case of significant liquid fuel shortages, government support of R & D on electric vehicles can be thought of as insurance, in contrast to the more usual investment in heat engine R & D.

Analysis of electric vehicle technology is complex, and depends in detail on the battery. The power and energy available from batteries are strongly dependent on a number of factors, and in particular must be traded off against each other, both in design and usage. This makes the range of electric vehicles, for a given battery technology, very dependent on how and under what circumstances they are driven. The range of electric

vehicles is therefore elusive, and many paper analyses have been made with erroneous or misleading results. 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.

The principal social value of the widespread use of electric vehicles would be the reduction of the dependence of the passenger car fleet on petroleum products. Thus, it would presumably lower the nation's dependence on imported fuels, as electric power will likely 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 for off-peak power. There are, however, important offsetting arguments: the availability of other means for 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-leveling at the electric power-plant 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 one 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 net value of such programs is positive.

The potential impact of the electric vehicle depends strongly on the question of its 'acceptability to vehicle drivers as a replacement of heat-engine-powered vehicles. There is substantial confusion as to both the range such vehicles will provide and the range which users will find acceptable. Unless these figures are in some proximity to each other, the electric vehicle will neither be adopted by private choice nor will governmental measures for its use be politically acceptable. An electric vehicle's "range" can easily vary by a factor of three among commonly used technical definitions. Furthermore, none of these definitions corresponds to what the electric vehicle user is likely to think of, namely the range he can be confident he will get on a given day. The technical definitions provide a standard set of conditions, but the vehicle user will encounter non-standard conditions (congestion, cold days, hills, etc.) where in his vehicle will not attain the technically defined range. The range of a vehicle in actual service will deteriorate from the range given for new batteries. The mere fact that he will often lose the freedom to extend his trip, once it has begun, will be an unattractive feature. Furthermore, we could find no statistical evidence indicating that second

cars are used significantly differently from first cars (in contrast to the often-made assumption that second cars are used for shorter trips). In our judgment a nominal range, as determined on the SAE Metropolitan Driving Cycle, of 100 to 200 miles is necessary for an electric vehicle to be close to competitive with a small used conventional car.

This "almost competitive" range for passenger cars cannot be attained by the available (or even plausible) lead/acid battery technology; might be attained by the nickel/zinc batteries now under development and possibly available within a few years; and can only be attained with any assurance only with one of several advanced batteries now in relatively early stages of development. Even if this range is attained, however, lead/acid and nickel/zinc vehicles will be far more expensive to drive than comparable ICE-powered vehicles.

Electric vehicles are significantly more attractive for usage in urban fleet operations. This is because: (1) maximum required daily ranges are reasonably short and highly predictable; (2) the fleet can be managed so that vehicles with older batteries can be assigned to less demanding routes; (3) battery exchange, maintenance and recharge operations can be centralized; (4) vehicle failure can be managed through routine procedures; (5) higher total usage per year makes the raw economics more attractive; (6) the vehicle can be tailored to meet particular fleet requirements; and (7) environmental gains are likely to be more significant due to the high mileage and urban locations of these fleets. Urban fleet operations are therefore the likely first candidates for significant electric vehicle usage, and in fact near-term (principally nickel/zinc)

technology may provide economical service in these fleets.

With these considerations in mind, we have reached a number of conclusions concerning appropriate roles for the government in supporting electric vehicle technology. First, over the long run (25 years or more), electric vehicles are an important, though not assured, prospect. Creation of an electric vehicle option would provide an insurance policy in the event that liquid fuel supplies, including synthetics, prove extremely expensive or limited. Second, a good case can be made for moderate Federal encouragement of a small but growing electric vehicle industry, so that development of the necessary infrastructure and non-battery technology would be undertaken. Third, there is little use in subsidizing passenger car operations with current lead/acid battery technology; in fact, such a program might inhibit future work in the electric vehicle area. Limited subsidies to demonstrations in fleet operations are more plausible. What is needed in the area of demonstrations is not an immediate action program, but a serious planning effort, looking at various possible markets, types of programs, etc. Fourth, the near-term technologies, especially nickel/zinc battery, may prove economically viable in some applications, but two domestic and several foreign R & D efforts are underway, and there seems little value to a government-funded R & D program. Advanced batteries which might allow the attainment of "almost competitive" passenger cars deserve consideration for government support. Two efforts are now receiving such support (the lithium/sulfur battery at ERDA's Argonne National Laboratory and the sodium/sulfur battery under NSF and ERDA support at Ford), some similar private (domestic) and foreign efforts

are underway, but support of one or more promising domestic efforts seems worthwhile. Sixth, and finally, substantial support of R & D on non-battery electric vehicle technology does not appear warranted as the battery is the crucial deficiency of present systems, and the improvement of other features of the vehicle will naturally occur when battery technology makes electric vehicles viable.

Closure - Alternative automotive powerplants potentially offer substantial benefits for American society in meeting the social goals of energy conservation and low air pollution levels. However, in contrast to the polar positions described in the Introduction above, the U.S. Government should neither commence an Apollo-style crash program for the development of production prototypes, nor should the Big Three be left to act on their own. Rather, we recommend that the Federal Government support R & D on some of the attractive alternative powerplants, but should always recognize that, without substantial Big Three involvement, government-developed automotive technology has little chance of making it into the marketplace. Detailed analysis of the many important sub-issues, and of the individual technologies, is difficult and uncertain, and calls for many judgements. But, on the whole, carefully selected government investments in alternative automotive powerplant R & D can be expected to pay off nicely in returns to American society.

PREFACE

This document is the second and last report resulting from a project conducted by the M.I.T. Energy Laboratory and supported by the National Science Foundation's Office of Energy R & D Policy. The first report, "The Role for Federal R & D on Alternative Automotive Power Systems" [1], was published in November, 1974, and contained the results of Phase I of the program, which began in June, 1974.¹ It examined the question: Is it appropriate for the Federal Government to support research and development (R & D) on alternative automotive powerplants? It was limited in scope, focussing on the question of whether or not such government-funded programs are appropriate, and did not evaluate in detail any of the individual powerplants or the programmatic or organizational issues involved in such a program. Past and current industry and government programs were examined, the critical issues laid out, the various possible objectives for Federal R & D examined, and the potential role of such a program as a policy tool (among others) for meeting the relevant national goals analyzed. The answer we then reported to this question was: "Yes, it is... appropriate for the Federal Government to support R & D on alternative automotive powerplants". This answer remains; no technological breakthroughs, changes in relevant national policy or other factors, or basic revisions in our own analysis have occurred which would cause us to change that conclusion.

¹Copies are available from the National Technical Information Service, Springfield, Virginia 22161 (order no. PB-238 771/OWE, price: \$6.25).

In this, our Phase II report, we focus in detail on Federally-supported R & D programs with the explicit objective of advancing the relevant technology. This is the most controversial of the possible objectives for Federal R & D; it potentially involves an unprecedented major public investment in the product technology of the nation's largest consumer product industry. The study examines three of the proposed technologies in detail (the Stirling, diesel and electric power systems) and broadens the analysis into some of the technological and structural issues and also into the stages of the technology introduction process not ordinarily considered "R & D". While we do summarize (and broaden in Chapter 3) some of the analysis of the Phase I report related to R & D for the purpose of advancing the state-of-the-art, we repeat little of the background information contained in the Phase I report or the analysis of R & D for the other objectives. Thus, while each of the two reports stands alone, they should be considered companion volumes.

This report is very much the result of a team effort. Every chapter received a detailed critical review, and often substantive inputs, from team members other than its principal author. We all stand behind the important conclusions of the report. However, we feel it appropriate to identify the principal authors of the three case studies. They are: Lawrence Linden for the Stirling engine, John Heywood for the diesel engine, and Howard Margolis for the electric vehicle. Also Michael K. Martin contributed to Chapter 3.

We once again express our appreciation to the great many individuals, in industry, government and academia, whose time and ideas were generously contributed to this effort. In particular we acknowledge Dr. Leonard Topper, formerly of the Office of Energy R & D Policy, National Science Foundation, who initiated the program and has been actively (and patiently) involved as contrast monitor.

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1. INTRODUCTION

Over the last decade the technology utilized in the passenger cars on American roadways has been the source of widespread public concern. This has resulted from the development of national goals, first for the reduction of the quantity of air pollutants in ambient air, and then for the reduction of the national dependence on imported petroleum, which changes in automotive technology must unquestionably play major roles in meeting. In the air pollution area, the American automobile manufacturers have significantly reduced the emissions from new vehicles principally by making small, evolutionary, year-by-year changes in their engines and fuel systems and introducing, in model year 1975, a minor technological innovation -- the exhaust catalyst. The fuel economy of domestically produced vehicles is also being significantly improved, with major reductions in vehicle weights (starting in model year 1977), new models (the Granada, Chevette, etc.) -- but again only minor technological changes, principally in the engine and drivetrain. This pattern is likely to continue over the next decade at least.

There are, however, significantly different systems, in particular, powerplants other than the carbureted spark-ignited Otto-cycle engine (or "internal combustion engine," hereafter referred to as the "ICE") which may offer the potential for significant and simultaneous improvements in passenger car pollutant emissions and fuel consumption. The "Big Three" American automobile manufacturers (the General Motors Corp., the Ford Motor Co. and the Chrysler Corp.) have investigated these alternatives and continue to conduct research and development (R & D) programs on them but,

unless a significant new initiative is taken somewhere in industry or government, it is not likely that any of them will reach the marketplace in the foreseeable future. The Federal Government's response to this situation has consisted, in part, of a relatively small R & D effort, principally on two alternative powerplants. The Federal program's purpose has been transitory and has never explicitly included the direct advancement of the state of the technology. The gap between the hopes and expectations raised by the potential societal value of some of the alternative automotive powerplants, and the actions of both industry and government have been the source of continuing controversy, and the ultimate genesis of this study.

This report addresses the question: Should the Federal Government support the development of alternative automotive powerplants? We specifically address the appropriateness of major new expenditures of public funds for advancing alternative automotive powerplant technologies with the explicit goal of significantly increasing the probability of their incorporation into future American passenger cars. As discussed at length elsewhere [1] (and briefly reviewed in Chapter 3), there are four objectives for which Federally-supported automotive R & D might be conducted: (1.) to advance the state-of-the-art; (2.) to support government procurement programs; (3.) to develop data for regulatory decision, policy formation, and public information; and (4.) provide "leverage" on private sector activity. Here we focus on the first objective, which is easily the most controversial, the most expensive, potentially the most significant, and certainly the most difficult to analyze, of the four.

By defining our central issue in this manner, we effectively exclude from consideration other approaches to meeting the relevant national goals for the automotive fleet, regulation in particular, from the set of decision variables we analyze. Thus we will take the general structure of the Clean Air Act as given, treat the schedule of emissions standards for future vehicles and its evolution over time as uncertain, and attempt to deal with our R & D question with this as a feature of the automotive picture. Similarly we treat government intervention through fuel economy regulations or incentives of some sort, beyond the present "voluntary" fuel economy improvement program, as uncertain.¹ We will only consider the impact that these regulatory activities (or other possibilities, such as new car taxes based on fuel consumption) have on the planning and implementing of possible government-supported programs. This is a reasonable approach because the (unfortunate) practice is that regulatory goals actually implemented have been set almost exclusively with the near-term "available technology" in mind. Because of the inherent time scales involved in the development, marketing and conversion to an alternative powerplant, the "available technology" (as previously defined²) has been and will continue to be that of the ICE-powered systems. Thus our report

¹At this writing a conference committee has just reported to the floors of the Houses of the Congress legislation containing mandatory average fuel economy standards for vehicle manufacturers' new car fleets [2], but the President has indicated that he may veto the legislation due to disagreement with its extended continuation of crude oil price controls.

²By the formal decisions of the Environmental Protection Agency's Administrators and the associated court cases under the Clean Air Act.

deals with the attempt to suboptimize, through R & D, a system with the other policy tools available to the Federal Government considered either constant or uncertain.¹ We hope this approach makes our report more useful to the R & D planners and approvers, who are the most important of our intended readers because, as implied in the above discussion, they have had relatively little influence over the regulatory processes.

At this point we would like to make explicit our view of the most useful and realistic approach a policy study of the sort we attempt here can take in its analysis of the respective roles of government and industry in American society. We accept the fact that the Big Three are economic entities, whose managements follow a behavior pattern which is in their and their firms' own self-interest (principally financial) as they see it, within the legal constraints imposed by the government. In this respect the Big Three's behavior is not different from that typically found in, or generally expected of, major American manufacturing oligopolies (or other firms), and there is little reason to suppose it would be so. In the particular case of the automotive industry, there are reasons to believe that there is in fact a significant gap between the Big Three's self-interest and that of society as a whole, even within present and anticipated legal constraints (such as the Clean Air Act); this source of gap will be explored at some length in Chapter 3. Our goal is, first, to understand how these firms operate within the legal, economic and technological environment they face (especially the key features of the process

¹In fact, we believe that a creatively designed regulatory or incentive structure might eliminate much of the justification for Federally-supported R & D, by inducing industry R & D, but such an approach does not seem to be politically viable.

of technological innovation in the industry), and then to determine how that environment can best be modified so that their self-interest is more closely aligned with that of society as a whole. In this report we examine how the government might change that environment through the support of the development of alternative automotive powerplants.

Since serious public debate on alternative automotive powerplants began in 1967 with the publication of the "Morse Report" [3] and a set of Senate hearings [4], the focus of most of the serious analysis has been the relative technical merits of the alternative powerplants and the ICE; analysis of the proper placement and structure of the interface between the public and private efforts has been relatively neglected.^{1,2} This has been a significant void: the issue is an important one in terms of the scale of the potential costs and benefits involved, and the government's minimally supported and ill-defined R & D effort has continued for six years without ever achieving a convincing or widely accepted justification of purpose (see Appendix A of [1]).

Within the last two years major advances have been made in the analysis of the technology with the development and application of techniques for comparing the alternatives as part of optimized vehicle systems [7,8],

¹See Section 4.1 and the appendices of [1] for a historical review of development of present industry and government programs and the accompanying debate.

²See Chapter 2 and Appendix B of [1] and also [5 & 6] for compilations of the technological and programmatic history and status of the alternative automotive powerplants.

and for making consistent forecasts of technological advances [8].^{1,2}

Lack of consideration of the entire vehicle as a system and inconsistent technology forecasts have been two major flaws of previous alternative powerplant comparisons. The recently released study by the Jet Propulsion Laboratory (JPL) [8], includes by far the most detailed comparative technological analysis of the alternative powerplants and the most comprehensive development of appropriate goals for R & D efforts that have been made to date. However, in its attempt to select the best powerplant, even it neglects (though not entirely) two important features of the problem; namely the tremendous uncertainties associated with the technology forecasts and the impact of industry practices on the attributes of any alternative powerplant which might reach the marketplace.

The focus of this report is specifically not on the technologies per se; we have performed no independent engineering analyses but rather have relied on the available data on the technologies we examined, as well as comparisons and analyses such as JPL's. As we will make clear, we believe that JPL's and others' similar results must be viewed in a perspective sharply tempered by the realities of the uncertainties involved and the likely industry behavior. We have explored these issues and the other key

¹The JPL report calls for a 10-year, \$1 billion R & D program to bring an alternative powerplant (the Stirling or gas turbine) to the marketplace; buried in their conclusions and not supported by any significant analysis or details is the recommendation that the government should "ensure that the program will be accomplished." [8; Vol. I, p.86]

²We acknowledge here a debt to the JPL report, whose publication preceded that of this report; their much larger effort allowed them to develop from basic sources many data for which we will reference them.

features of this very rich problem in our analysis of what the Federal Government should do (if anything) in advancing these technologies.

Our analysis of this issue is laid out in the following manner. First, in Chapter 2, we step back from our focus on government R & D and look at the automobile market as it exists today (specifically: without a major government-supported R & D program). The key features of the automobile manufacturers, automobile consumers, and the present government regulatory intervention, are examined for their implications concerning major technological product changes. In particular the process of technological product innovation in the Big Three is discussed and a simple model laid out for use in the subsequent analysis, because it is the Big Three as we know them today which will be the ultimate designers and producers of any alternative powerplant which makes it to the marketplace.

Next, in Chapter 3, we address the general features of the Federal R & D decision. First, the various possible objectives of government-supported R & D on alternative powerplants are considered. Utilizing the material developed in Chapter 2, we then focus on the issue of whether or not there is a significant gap between the private and social costs and benefits of long-range automotive powerplant R & D -- we consider the clear existence of such a gap a necessary (but certainly not sufficient) condition for government support of alternative powerplant development for the purpose of advancing the state-of-the-art. The conditions under which a socially-beneficial government-developed powerplant might be brought to the marketplace (i.e. "commercialized") and the implications of this issue for R & D project selection and program design are subsequently

addressed (Chapter 2 again provides key background). Next we examine the limitation imposed by a number of key uncertainties in the analysis of the government's R & D decision. Finally, some general criteria for the choice of technologies and program design are laid out.

In Chapter 4 one of the critical uncertainties -- the technological evolution, over the next decade, of the "baseline" system, the ICE -- is examined in detail.

Three case studies of government support of individual alternative power systems are then presented. They are attempts to apply and demonstrate the general features of the analysis of Chapter 3, viz. both to utilize the analysis and to demonstrate its limitations. The alternative power systems can be divided roughly into three categories; the three cases were chosen to represent these categories.

In Chapter 5 the Stirling engine is examined in detail. It represents the first class, the advanced heat engines; the other prominent members of the class are the Rankine cycle and gas turbine engines. Each offers potentially significant improvements over the ICE in either vehicle fuel economy or pollutant emissions or both, but would require a substantial development program before it could be mass-produced at reasonable cost in a configuration demonstrating its potential advantages. Major changes in the manufacturing processes and thus the equipment used by the automotive industry would be required. These engines could not be in mass production in suitable configurations for at least a decade. The Stirling engine is addressed as follows. First the status of the present (and likely future, near-term and long-term) technology and R & D programs are reviewed (the details of the

technology are relegated to Appendix A). After some discussion of the proper method of comparing automotive powerplants, the social costs and benefits of government-supported Stirling engine R & D are examined to determine the likelihood that such investment has a positive expected net present value. A simple model for the total operating costs of the Stirling engine, relative to the contemporary (1985) ICE, is utilized. Finally, the issue of commercialization and program design are addressed.

Next, in Chapter 6, a case study of the diesel engine is presented. It is typical of those alternatives which, generally speaking, are not too dissimilar from the ICE. The Wankel spark-ignition engine and the various types of stratified charge engine can also be considered members of this class. Some of these potentially offer a vehicle fuel economy advantage over the ICE, but none offers obviously substantial improvements in air pollutant emissions. They would not require the use of manufacturing processes significantly different from those used for the ICE; and they may be considered as technology which either is available now, or could be in the next few years. Our analysis of the diesel begins with a review of the technology and present R & D programs, including an examination of present diesel engine production and usage, and an assessment of the trade-off between vehicle fuel economy and performance. The factors influencing the process by which a domestically produced diesel-powered passenger car would be introduced into the American marketplace are next addressed. Then the appropriate roles for the U.S. Government in supporting R & D on the diesel are discussed.

The last class of alternative automotive power systems is that of the electric vehicle; it has a number of properties which make it very different from the various heat engines. The technology itself is very different and would virtually require the establishment of a new battery manufacturing industry. The attributes of electric vehicles are different from those of vehicles powered by the heat engines, resulting in very different environmental and energy impacts; and, due to the inherent range limitation of electric vehicles, very different consumer acceptability issues are raised. Our analysis begins again with a review of the technology and current R & D programs. The social value and issues of consumer acceptability are next examined. Finally we look at the appropriate role for government-supported R & D.

It would be desirable to develop a methodology for determining an appropriate government role which would be general enough to apply to any alternative powerplant. In fact, for reasons which will be made clear in Chapter 3, this is not possible. We consider, therefore, that the case studies we present in Chapters 5, 6 and 7 are at least as valuable as the more generally applicable descriptive and analytical material in the earlier Chapters.

A number of recent developments have significantly raised the level of interest in the alternative automotive powerplant issue. The recent dramatic increase in the price of petroleum products has caused a reevaluation of all fuel-conserving technologies, including a number of the alternative powerplants. The Energy Research and Development Administration (ERDA) has now received an explicit charter

for alternative automotive powerplant R & D which its predecessor in this area, the Environmental Protection Agency, never had, and is in the process of completing its review in the place of alternative automotive powerplants in its R & D portfolio. A bill has come out of conference to the floors of the Houses of Congress containing a major new Federal initiative in automotive R & D [2], and a bill specifically supporting an electric vehicle R & D program has passed the House of Representatives. [9] The massive report by JPL was released in August, 1975, containing a comprehensive technological analysis of the alternative powerplants and the recommendation for a national commitment to a major R & D program on the Stirling and gas turbine systems. That report has been the focus of great interest and controversy within both industry and government. Finally, the Executive Branch of the Federal Government is involved in a comprehensive analysis of goals for the automobile beyond 1980, the "300-Day Study", which includes an examination of the place for alternative powerplants. Clearly it would be rash to predict that these factors will force (or even allow) a resolution of the continuing question of whether or not the major R & D programs are necessary to give an advanced alternative a place in the foreseeable future of our society will be undertaken, either by industry or government. We hope, however, that our study contributes constructively to an informed and realistic public debate.

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2. THE PROCESS OF MAJOR TECHNOLOGICAL PRODUCT CHANGE IN THE AUTOMOBILE INDUSTRY

The "automobile industry" is a vast system of firms for manufacturing and selling new automobiles, and producing and distributing the myriad of supplies and services required for the nation's roughly 100 million passenger cars. Broadly defined, it consists of about 600,000 separate establishments, with a total employment of over 4 million people who receive about \$20 billion in annual wages, and absorbs 13% of Americans' personal consumption expenditures.¹ The keystones of the industry are the General Motors Corporation, the Ford Motor Company and the Chrysler Corporation, the second, third and eleventh largest manufacturing concerns (by sales) in the United States, respectively [11], collectively referred to as the "Big Three". These three manufacturers presently produce well over 90% of the automobiles made in the United States and about three-quarters of the automobiles sold here. The technological features of the product they decide to build determine the fortunes of little and large firms in the automobile parts and service industry, have major impacts on the demand for domestically supplied and imported minerals, determine a major share of the demand for refined petroleum products (and thus are an important factor in the aggregate demand for crude oil), are a key factor in the highway death and injury toll, and have a major impact on the quality of the urban air Americans breathe.

In this chapter we will examine the process by which changes are made

¹The automotive-related portions of the petroleum industry are included in these figures. [10, pp.52, 59]

in the key technological features of this most important product, the American automobile. We will focus on the decisions of the Big Three, with lesser attention given to American Motors Corp. (AMC, the fourth domestic passenger car manufacturer), the foreign manufacturers, the component suppliers, dealers, repair shops, etc., for it is in the headquarters buildings of the Big Three in Detroit that the crucial product decisions are made. We will be concerned only with major technological product changes, whose impact is of the order of that of a change to a new powerplant. We will not, in general, be concerned with product changes of lesser impact, nor will we deal with process innovations (i.e., changes in manufacturing technology), except insofar as they are a necessary or ancillary factor in major product changes or shed light on the process by which major changes are made. The forms of automotive product change which receive the most attention are the "annual model change" (i.e. style changes made almost annually to most models) and "new models" (i.e. cars of new design, such as this year's Chevette), but because these generally involve little in the way of new technology they are of little direct concern here.

The general aim of this chapter will be to describe the crucial features of the "ball game" in which the Federal government will be playing if it is to engage in a substantial automotive R & D program. Subsequent chapters of this report will utilize this background material in their discussion of alternative powerplants. This chapter is laid out as follows. In the first section we will discuss those features of the present market for passenger cars, including the present government involvement, which have important influences on the process of automotive technology development

and production.¹ In Section 2.2 we develop these influences and draw some conclusions concerning the key features of the process of TD&P. Then, in section 2.3, a simplified model of the process itself will be laid out which divides it into stages of activity with intervening decision points. Finally, in Section 2.4 we will close the chapter by drawing some preliminary conclusions which look ahead to the discussion of government R & D in the remainder of the report.

2.1 Present Market Structure and Government Involvement

The American passenger car market combines a set of features which make it unique among the major American industrial markets. These features are of crucial importance in determining just how the Big Three select, develop and implement changes in their product. In this section we will (rather quickly) examine these features. We will lean heavily on the work of White [3], whose study, The Automobile Industry Since 1945, is the most comprehensive economic treatment of the industry available.

For simplicity, we will generally refer to the "Big Three," as if they acted identically and as a unit. While this is often true enough, there are in fact important differences between the three firms. Probably the most important is the difference in profitability and thus in ability to support innovation. In recent years GM, Ford and Chrysler have maintained a profit per car sold in the ratio of about 4:2:1, respectively,

¹We will use the shorthand "TD&P" to refer to the process of "Technology Development and Production" in the industry, extending from initial R & D through mass production.

[12, p.266] and unit sales in roughly the same ratios. [10, p.10] Thus Ford and Chrysler could be hard-pressed to finance innovations at the same rate as GM, and Chrysler in particular has given the appearance, and in fact admitted [13, p.1586], that in the last couple of years it has not been able to match the investments of GM and Ford either in R & D or in new product development. There is, of course, a fourth domestic passenger car manufacturer - the American Motors Corporation. While on most scales AMC would be considered a large corporation (annual sales approaching \$2 billion), it does little R & D and is generally a follower in the area of major technological product changes (although this has not been as true in other forms of product innovation).

Four features of the automobile market have significant influence on the TD&P process: on the supply side, (1.) the industry's manufacturing processes are highly capital intensive and (2.) the industry is highly concentrated; (3.) the demand for passenger cars is highly variable, both in quantity (over time) and in its response to technological features; and (4.) the present government regulatory structure adds uncertainty and significantly affects the industry's planning horizon. These four features interact strongly. In the following paragraphs each feature will be defined and discussed separately. Their interactions will be addressed and their separate and overall implications for major technological product changes will be discussed in the next section. Many other interesting features of this complex industry, which certainly have at least some impact the process of technological change, will not be addressed here (e.g. the relations between the Big Three, their dealers and the automotive parts aftermarket; the internal corporate structure of the Big

Three; the Big Three's overseas operations; etc.).

The basic structure of the supply side of the market, i.e., the Big Three and their process and product technology, has been in a state of steady evolution since the late 1920's. This period of relative stability was preceded by several decades of dynamic technological and entrepreneurial competition, during which the basic product in use today (i.e. vehicles which are covered, use four wheels and an ICE, etc.) emerged technologically, and the Big Three came out the winners on the business side. As long as gasoline prices were relatively stable and affected only a small fraction of operating costs, and pollution control was not an issue, technological product change was undramatic but significant, and the performance, fuel economy, handling, initial cost (relative to value received), etc., of today's car are substantially superior to those of fifty years ago, even if most of the major features are similar.¹

The massive expansion of the market and the lack of a requirement to be able to make major technological product changes rapidly led to a focus on cost reduction and thus a tremendous investment in automatic machine tools as the preferred manufacturing technique.² For example, a modern engine manufacturing plant utilizes many such machines. The basic inputs to the plant are the raw iron castings, from the foundry, of the major engine components -- the block, cylinder head, pistons, etc. Each

¹See Ford [14, p.2676] and Leeth [15] for some quantitative discussion of these evolutionary advances.

²See Abernathy and Wayne for a discussion of this development in the context of the market strategies of Ford and GM [16].

component enters a "transfer line" in which it is automatically moved from one machine to the next, with each machine performing one or more automated operations (drilling, broaching, milling, etc.) until the completed component is delivered to the engine assembly line. As many as 500 separate automatic operations may be performed as, for example, a newly cast block with the right general dimensions is converted into a precisely honed complex web of holes and spaces [17, p.C-3]. An engine plant generally makes only one specific engine; modern plants have a production capacity up to about 500,000 units per year. Economies of scale in engine manufacture are estimated to be obtained by plant capacities up to about half this size. [12, p.24] Most of the other key manufacturing and assembly operations are highly automated (and thus capital intensive) as well.

It is worth mentioning another form of capital which has been accumulated by the automobile industry -- namely the wealth of knowledge and experience accumulated in decades of dealing with the ICE. As recently discussed by Gilpin [18, p.1-2] (among many others), such knowledge, much of it implicit and unrecorded, is representative of a vital component of an advanced nation's capital stock. Much of this part of the automotive industry's capital stock would be very expensive to recreate in a transition to an alternative powerplant; the R & D programs discussed below would be the first steps of this replacement.

The second key feature of the supply side of the market is the fact of its concentration. During the period of relative stability the number of "independent" (i.e. non-Big Three) domestic manufacturers fell from 12 in 1929 (with a total market share of 17%) [19, p.141-2] to the single one

remaining (AMC). With only three firms presently accounting for about 95% of domestic production and 75% of domestic sales, each must carefully account for the reactions of the other two when making any significant marketing decision. The high barriers to entry in the automotive manufacturing business [12, pp.54-77] make the Big Three secure from new domestic competitors; and AMC and the imports, while capturing (at present) about one-quarter of the market, barely attempt to compete directly with the Big Three in what remains the largest selling segments of the market -- namely cars in the intermediate and standard size classes.

In pricing the result of this concentration is relatively clear, as the high profitability and price leadership of General Motors has been well documented (e.g. by White [12]). In general, the effect of industrial concentration on technological change has been widely debated among economists and little in the way of consensus has been reached.¹ Similarly, there exists substantial debate concerning the relative technological progressiveness of product change in the automobile industry, with much speculation or assertion that the industry has been overly slow.² [e.g. 12, 20, 21, 22, 19] It is impossible to resolve this issue because, of course, there is little with which to directly contrast the in-place technology. Here, however, we are not so much interested in the general issue of progressiveness as in the effects of concentration on the process

¹See Scherer [23] for a comprehensive discussion of the arguments and some tentative and very general conclusions.

²White concludes that "In manufacturing technology, the companies' record of progressiveness seems fair to good," in contrast to the view of many of their record in product technology. [12, p.256]

of TD&P; this will be addressed in the next section.

The demand side of the automobile market also has great influence on the process of automotive TD&P. Most significantly, the demand for automobiles is highly variable, both over time and between vehicle attributes. The automobile is a consumer product and its purchase typically represents the second largest made by an American family. Thus the three huge firms must satisfy the various tastes and needs of millions of individual customers; as auto industry spokesmen like to pose the contrast: "Automobiles may be made by the millions, but they are sold one at a time". Furthermore, as a result of the high degree of optimization obtained during the lengthy period of stable evolutionary development, automobile purchasers have developed high expectations for their automobiles.

The temporal aspect of the demand is due to the fact that it is almost entirely a replacement demand: in the last decade U.S. sales have been in the range of 8 to 11 million automobiles annually, while the domestic vehicle fleet has been growing at the rate of 2 to 4 million annually. [24, p.10,71] The new car buyer, therefore, generally has the alternative of keeping his present car longer rather than buying a new one. Thus price increases (or quality decreases) which occur simultaneously throughout the industry, or national economic disturbances, can result in significant short-term decreases in industry-wide sales.¹ This has been painfully evident in the last two years as price increases in automobiles and gasoline and reduced personal income sent the auto industry into its

¹Although the statistical evidence is ambiguous, it appears that the short-run elasticity of new car demand with respect to price is considerably higher than the long-run elasticity. [12, Chap. 7 and Table 7.2, and 25, pp. 66-69].

worst slump since World War II. It has been suggested that the degraded driveability due to emission controls, the mandatory installation of unwanted safety devices, and other negatively-perceived impacts of government regulation, have made consumers less eager to part with their older vehicles, also contributing to the present slump.

Consumer reaction to technological product change is hard to predict, as witnessed by the two-year lifespan of fuel-injection and air suspension in the American market in the late 1950's.¹ And who could have predicted the popularity of vinyl-covered roofs, for which 49% of new car buyers in 1973 paid roughly \$100 each? [10, p.23] It is often stated that the automobile industry (among others) controls the demand for its product, principally through advertising [e.g. 27, p.215], and no doubt this is to some extent true. As seen here, however, substantial uncertainty in forecasting consumer demand is the fact evident in the market today.

Along with the usual supply and demand forces in the automotive marketplace, today there is a third factor which has a key impact on the process of automotive TD&P: the Federal Government. Of most direct relevance is the possibility of legislation mandating fuel economy standards.

A brief discussion of the history of the Clean Air Act and its implementation indicates the type of government involvement the industry must deal with in its TD&P process. The 1970 Amendments to the Clean Air Act were adopted by an overwhelming majority in Congress, and stringent air

¹Air suspension was offered by Ford and GM (and AMC) in model years 1958 and 1959, achieving a total market penetration of 2.3 and 0.5% in those two years, respectively. [26, p.33] Fuel injection was marketed by GM (and AMC) in model years 1957 and 1958 and by Chrysler in model year 1958 (and presently appears to be in the process of making a comeback).

pollutant emissions constraints were written into the law. Unfortunately, the evidence to justify the particular levels chosen for emission standards was weak: health studies were sparse, instrumentation was primitive, the relative importance of automobiles and other sources not well known, and the analysis of the dispersion and chemistry of air pollutants in urban atmospheres only partially understood. By the same token, the deadlines for achievement of the standards were set without precise knowledge of which technological solutions were feasible or how long the process to their implementation would take. Essentially the law set goals and short deadlines not only to force implementation of new technology, but also to force the development of the appropriate technology itself.

As it has turned out, the manufacturers have not been able to meet the hydrocarbons (HC) and carbon monoxide (CO) standards originally set for 1975 or the oxides of nitrogen (NO_x) standard set for 1976. In 1973 the manufacturers were granted the one-year extensions in the deadlines provided (conditionally) under the law; for each pollutant, interim standards were set which were more stringent than the former standards but considerably more lenient than the full 1975-76 restrictions. By 1974, it seemed clear that the original 1975 standards for HC and CO could not be met even by the 1976 date to which they had been administratively postponed, and Congress passed further amendments to the Act. The deadline for HC and CO was postponed to 1977 and for NO_x to 1978, and the Environmental Protection Agency (EPA) Administrator was given the discretion to grant, and has subsequently granted, yet another one-year extension for the HC and CO. Throughout this period, however, the ultimate statutory standards (3.4 g/mile of CO, 0.41 g/mile of HC and 0.4 g/mile of NO_x) have remained

unchanged, even though the need for each has been seriously challenged. In the case of NO_x standard the EPA itself has called for a change in the standard because of errors in the measurement technique used to determine ambient levels of the pollutant. To date, however, no change has been approved by the Congress, although a large number of credible proposals have been made and (at this writing) legislation is pending.

The crucial features of this type of regulatory program are: (1.) mandatory standards which are not known either in the short-run (e.g. it is expected that the present 1978 emissions standards will be revised) or in the long-run (e.g. the NO_x standard), (2.) the short-run standards are set to the limits of the "available technology", and (3.) every car produced in a given model year must meet the same standard. Automotive safety and damagability legislation and its implementation contains similar features. It is becoming clear, after almost a decade of national automotive regulation, that stable long-term regulatory standards may never come into existence.

Beyond the present regulatory involvement, the Big Three have been under considerable pressure to explain and justify various features of their product technology, especially before Congressional Committees, with wide attendant publicity and the implied or real threat of new government interventions in the automotive market.

The most obvious and important impact of such a regulatory program is to add one more uncertainty to the technological requirements to be met by relevant future technologies. On a more general basis, the Big Three must account for the government's reactions to new technological developments just as they must now account for each others' and the public's

reactions.

2.2 Implications for the Process Of Automotive TD&P

In the previous section we described the present structure of the passenger car market, emphasizing those features which have an impact on the process by which major technological product changes are made. In this section we will address those impacts, taking into account the interactions of the market features discussed above.

The high degree of capital intensity in the automobile industry, along with its decades of exclusive production and continuous evolutionary development of present product technology, make the industry naturally slow in its ability to respond to new technology or to a new environment by making major technological changes in its product. This is reflected in several ways in the process of TD&P. First, it implies that a lengthy R & D process will necessarily precede any marketing of a new or substantially altered product. This is because the innovation must show a substantial advantage relative to the in-use product, which has already attained a high degree of optimization. Further, it must meet these technical demands at the low costs attainable only under highly automated production. Thus a successful R & D program must also include a major effort in optimizing the new product for low cost mass production and in performing the associated process engineering. Second, these lengthy R & D programs, plus the initial tooling required to introduce an innovation to the marketplace, make major technological innovations very expensive. Most of this investment must be made before the first mass produced units can be tested in the

market. Third, the large amount of tooling required for mass production means that, once an innovation has proved successful in the marketplace, capital and tooling availability may limit the rate of production build-up. Finally, the major investments in the R & D and tooling imply the desirability of a stable product demand to provide sufficient production for investment recovery and profit.

The impact of the concentration of automotive production in the Big Three is less clear. Obviously each firm carefully watches the other two in order not to be left out of a significant change. There has often been a "bandwagon" pattern of behavior where any potentially attractive innovation is brought out almost simultaneously by two or more of the Big Three. Generally the initiator of a major innovation cannot even count on the normal production lead-time of 3 to 4 years because the flow of information between firms, through various means, makes it very difficult to conceal the intense final stages of development, purchases of special tooling, etc., which signal the impending introduction of the innovation. Thus, for example, even in the case of the two unsuccessful innovations mentioned above, fuel injection and air suspension, at least two of the Big Three introduced them almost simultaneously. This behavior has not been universal; for example neither Ford nor Chrysler followed GM's recent procurement of tooling for the Wankel engine because their own evaluations led to determinations that the Wankel would not be a success. This tendency toward a commonality in the product technology has in the past often been explicit -- the auto industry has had a history of extensive cross-licensing of proprietary technology [12, pp.213-5], and it is unlikely that this pattern of behavior will not apply in the future. Each case of a

major technological innovation will, however, follow its own course. Major technological changes in "mature," concentrated, industries whose product changes have primarily occurred through slow evolutionary process, have often been accomplished through invasion by new firms (or firms from other industries) more willing or able to exploit a new technology. [28] This has been seen to some extent in the American automobile industry as the Wankel and pre-chamber stratified charge engines have first been marketed here by foreign firms, Toyo Kogyo and Honda, respectively, both newcomers to the automobile industry (neither firm engaged in significant automobile production before 1960 [28]). Vigorous technical investigations by the Big Three following these minor beachheads, indicating their willingness and ability to successfully respond to technological threats [1, Appendix B]. These examples serve, also, to indicate the role of the imports as catalysts of technological change.

The variability of automobile demand leads the manufacturers to pay great attention to "pleasability," i.e. those technologically unimportant attributes to which the manufacturers pay so much attention -- like the sound of a closing automobile door, the exact color coordination of different materials in the vehicle interior, etc. Naturally this shows up in the TD&P process; for example in both the disc brake and power steering development programs major efforts were made to keep down irritating noises -- efforts very possibly as important to the ultimate success of the programs as the basic technological attractiveness of the innovations.

Finally, and most importantly, the structure of the passenger car market makes technological product change a very risky business. The combination of the long lead time involved in bringing an innovation to

the marketplace and the unpredictability of consumer and (where relevant) government demands, mean that the probability of failure, or "pure risk", cannot be reduced below some minimum, significant level. The tremendous investments which must be made before success or failure is determined mean that the "dollar risk" (investment times probability of failure) involved in a major technological product change may be large enough to have a perceptible impact on the firm's near-term accounting profits.

This feature has significant implications for the process of TD&P, because the firms will attempt to reduce the dollar risk involved in an innovation. We will develop this point at some length because it has not been widely recognized. The impact of the high dollar risk on the decision of whether or not to invest in an innovation is obviously inhibitory. Once having decided to bring an innovation to the market, the firm has substantial incentives to reduce the dollar risk by reducing both the probability of failure and the initial investment in the innovation. The steps taken to reduce the probability of failure are the usual ones, especially field testing, usually in fleet vehicles, prototypes and early production output.

More significantly, the Big Three strive to reduce the initial investment required for the innovation. This is typically accomplished in two ways. First, they may initially produce the new or changed product at a limited volume of production that may be well below the most economic level (which is in turn likely to be well below the ultimate production level if the innovation is successful). Thus the investment in tooling is held down, but the cost of the product is above (and possibly far above) its cost at higher production volumes. Even at the early limited

production levels, the firm may choose a production technique which is less capital intensive than optimal, in order to hold down the fixed cost of the innovation.¹ In the case of the front wheel disc brake, for example, Ford's introduction was made in model year 1965 as the new brakes were made standard on the Lincoln and Thunderbird and optional on the Mustang. With demand thus artificially limited, initial production involved the use of expensive hand assembly of the caliper components. [29,30] Within three years, as the performance features of the brake made it a popular item, a new brake was designed which, among other things, received careful production engineering for minimizing the total cost at high output.

The second technique for reducing the fixed cost of an innovation is to design it so that it involves minimal disruption of other vehicle systems, i.e. so that it has a high degree of "integrability."² Again there may be an important trade-off -- either compromising the performance of the new product so that it fits the vehicle without significant vehicle changes (but perhaps sacrificing some information on its long-run potential demand), or investing in vehicle changes and increasing the capital risked on the innovation. This trade-off will be discussed again elsewhere in this report because it has major implications for the introduction process which would be used for an alternative powerplant whose

¹ Thus the firm faces the dilemma of whether to price the innovation at full cost, thus not getting a good indication of ultimate demand and risking failure due to low demand, or it may price the innovation at the estimated long-run cost and absorb the difference.

² The modern automobile is a complex and highly integrated piece of machinery, so that little changes made at one point may require simultaneous changes at many other points throughout the system. For example, Peter Ware [31] lists the numerous changes which would result from a change in wheel diameter.

power density was significantly different from that of the ICE; and thus had a low degree of integrability.

These efforts to reduce the initial investment, both in production equipment and design effort, imply that substantial product development will likely continue after a successful introduction. At first, the advantages of the innovation may be compromised to minimize the dollar risk while gaining information on demand. If successful, specialized tooling and vehicle redesign are likely to follow when demand is relatively well-known and the system is optimized with respect to cost and performance.

2.3 A Simple Model Of The Process Of Automotive TD&P

In this section we will focus the previous discussion of this chapter into a model of the process of TD&P in the automotive industry. It will incorporate and organize the features of the TD&P process previously discussed and provide a set of definitions for use in the subsequent analyses of the report.

We have chosen to model the process of TD&P as four discrete "stages" of activity with a "decision" made by the firm before each stage as to whether or not to advance the innovation into it. Our discussion of the model interleaves the usual six stages of R & D (Basic Research, Applied Research, Exploratory Development, Advanced Development, Engineering Development, and Product Improvement) with the three phases of the technology substitution process (development, market introduction and

penetration, and vehicle substitution).¹ We would like to follow a given product change through the process, describing what sort of effort is made during each stage of development and what the key criteria are in the decisions.²

The development of a simple model is fraught with difficulties. First oligopoly behavior in general remains an area of active research, even in such relatively "simple" areas as pricing. Similarly, studies of technological innovation have not developed very many well defined behavioral rules, even for the "simple" cases of perfect competition or monopoly. Thus the academic fields are of limited help in our examination of technological innovations in an oligopoly. Furthermore, there is only a limited amount of useful historical data on past automotive industry innovations. The principle reason is one which is obvious from the discussion in the previous section of this chapter: the development and market introduction of an alternative powerplant would represent a technological product change of greater magnitude than any since the pre-World War I days of the industry. The industry has introduced "new" "models", risking (and sometimes losing) sums of magnitude similar to that involved in a new powerplant. These new models, however, have involved little new technology. The only technological product innovation since World War I which approached the significance of a new powerplant was the automatic transmission, which

¹These were discussed separately in Sections 1.4 and 3.4 of [1].

²See Mullins [32] for a general discussion of the continuum of industrial decisions from R & D to plant investment, a somewhat unique effort to bring together the two generally separated fields of R & D management and corporate finance.

was first marketed in the late 1930's and reached substantial market penetration and relative technological stability in the mid-1950's. While the early developmental history of the automatic transmission [e.g. 33] and the subsequent technological history [e.g. 34] have been discussed in the open literature, there is virtually nothing in the way of discussion of the industry decision-making process. Our model will, however, utilize the case study on the disc brake [35] and other sparse data available on previous innovations. The relevance of even this limited historical material is limited by the very nature of the issue at hand, viz. never before has government involvement in the process of passenger car TD&P been undertaken to the extent contemplated here.¹

Our model will therefore be based on the available historical data, some relevant work in previous studies of the alternative automotive powerplants issue [8, 17, 36], information obtained in interviews with the Big Three and other organizations involved with alternative powerplants, and our knowledge of the industry's attitudes and practices. The model will be no more than a crude schematic of a very complex, evolutionary process. It will suffer from the usual defect of such models in that it will probably not apply directly to any specific innovation, or even any specific alternative powerplant. It will, however, capture and lay out the principal features of the automotive TD&P process.

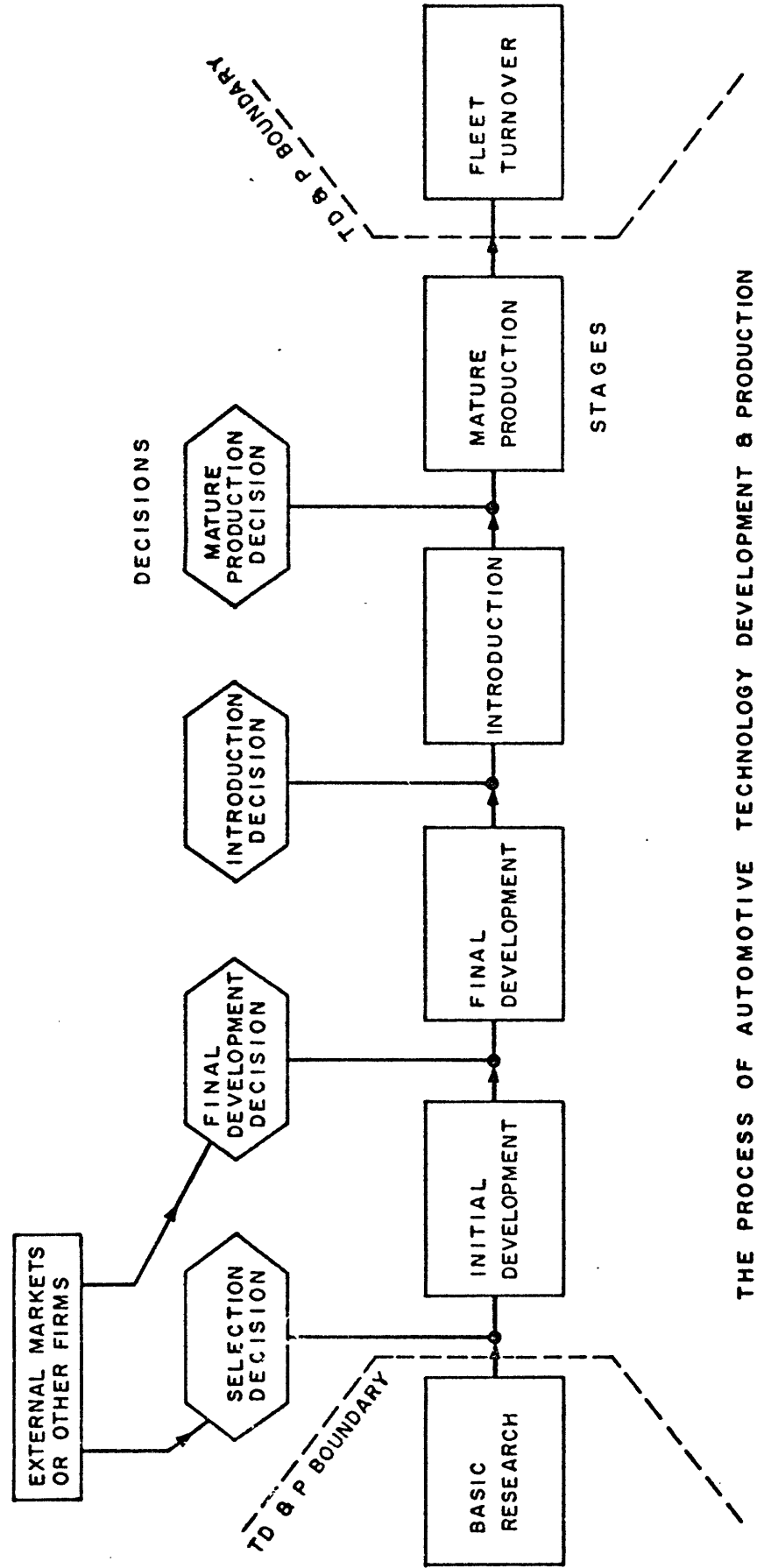
¹There was, of course, massive federal involvement in the development of armament production capacity in the automotive industry in World War II, but this was for the objective of meeting government procurement needs rather than changing the private passenger car.

Figure 2.1 shows the stages of automotive product TD&P and the intervening decisions which together compose our model.¹ Each stage is designed to advance the technology and provide the information at the end of the stage for an appropriate decision to be made concerning its future. A successful product innovation proceeds through the process; during each stage the firm invests in the relevant R & D, engineering, or plant and equipment, so that at the end of stage the success criteria for the subsequent decision are met. Defining failure is much more difficult and will be addressed below. Tables 2.1 and 2.2 provide the key features of the four decisions and stages.

We are interested here in technological changes in the passenger car pretty much as we know it today. Thus any innovation, even a new engine, is almost surely a replacement for, or modification to, some system already in production. The advantage of the innovation may be one of cost alone, with no perceptible performance change. The TD&P process, as we have described it, focusses on innovations which offer some technological advantage at the same initial cost or, more likely, some premium (as will be seen below, this is the type of innovation we are interested in).

In general we will focus on the process as it applies to development by a single firm. This would be a tremendous simplification if it were taken literally; each innovation follows its own course through the web of industry connections. Much of the discussion will apply, therefore, to the

¹A note on terminology: In subsequent chapters we will often use the term "commercialization." This refers essentially to the Introduction Stage, i.e. those actions taken to bring the completed result of an R & D program into the marketplace. The "commercialization criteria" are those of the Introduction Decision discussed here.



THE PROCESS OF AUTOMOTIVE TECHNOLOGY DEVELOPMENT & PRODUCTION

Figure 2.1

Table 2.1

DECISIONS IN AUTOMOTIVE TD&P PROCESS

<u>Decision</u>	<u>Key Decision Criteria</u>	<u>Relevant Uncertainties</u>	<u>Risk Aspects/Decision Process</u>
1. Selection	Some potential technological (or cost) advantage over in-use system. Actions of others of the Big Three. Government pressure.	Performance. Product Cost. Demand, actions of others of the Big Three, and government behavior forecast for at least a decade in the future.	Individually risky, but diversification possible due to large number of projects and low individual cost. Highly judgemental.
2. Final Development	Superiority on at least one technological attribute and at least equality on others. Cost feasibility. Actions of others of the Big Three. Government regulation or other strong pressure.	Product cost. Demand, actions of others of the Big Three, and government behavior up to a decade in the future.	Decreased diversification and higher individual project cost but lower individual probability of failure. Highly judgemental, risk analysis may be applied.
3. Introduction	Long-run profit potential. Actions of others of the Big Three. Government coercion. Capital availability.	Consumer response in several years, government response in long-run. Performance in actual widespread use. Product cost well-known.	Little or no diversification, and finite probability of failure due to consumer response and high cost make it very risky. Capital budgetting with risk incorporation may be used.

Table 2.1 (Cont'd)

<u>Decision</u>	<u>Key Decision Criteria</u>	<u>Relevant Uncertainties</u>	<u>Risk Aspects/Decision Process</u>
4. Mature Production	Profit potential. Capital availability.	Demand over long-run. (Product cost and short-run consumer response well-known.)	Risk reduced to minimum, i.e. forecasting aggregate vehicle demand and disaggregation into firms and specific products. Capital budgetting procedures used.

Table 2.2

STAGES OF AUTOMOTIVE TD&P PROCESS

<u>Stage</u>	<u>Technology Status</u>	<u>Key Activities</u>	<u>Features</u>	<u>Comment</u>
1. Initial Development	Several alternative configurations under consideration.	Proving technical feasibility and improving performance with little emphasis on product cost. Work on components and subsystem integration. May end with "proof-of-concept" demonstration in vehicle.	Many projects underway but each of relatively low cost.	Includes Applied Research, Exploratory and Advanced Development stages of R & D.
2. Final Development	One configuration chosen as best.	Focus on cost reduction through design optimization and manufacturing choices while maintaining demonstrated technical advantages. Extensive testing including in vehicles, possibly by selected consumers. Aim for integrability and pleasability.	A few projects underway, each an order of magnitude more expensive than I.D. projects.	Includes Engineering Development and Production Engineering.

Table 2.2 (Cont'd)

<u>Stage</u>	<u>Technology Status</u>	<u>Key Activities</u>	<u>Features</u>	<u>Comment</u>
3. Introduction	Configuration offered may be less than long-run optimum.	"Soft" tooling procured and production initiated. Feature introduced as option on one or several model lines. If government-required, then initial production may cover all vehicles. Marketing campaign. Extensive internal coordination required, including distribution of service literature, etc. Extensive testing of first production units, probably in fleets on model year before market introduction.	Another order of magnitude investment increase.	Firm seeks to minimize risk by trading off initial investment in vehicle redesign and tooling against initial production cost and performance.
4. Mature Production	Long-run optional configuration approached.	Building of plants with minimum total cost of production (highly automated). Incorporation of consumer feedback on design. Offer as option on virtually all models, if make standard on some, if not government required. Redesign for optimum with vehicle modifications.	Another order of magnitude investment increase.	Includes Product Improvement, i.e. minor modifications to the new system. Ultimate market penetration may or may not approach 100%.

industry as a whole, including the Big Three and their component suppliers. On a number of past innovations, for example, much of the initial development work was performed by suppliers. When read as applying to the industry as a whole, the stages become more diffuse as one firm may lead the others by a year or two, or one of the Big Three may decide not to participate in a given innovation.

The decision criteria listed in Table 2.1 are of course ambiguous; they must of necessity be made more specific in a real instance, even if the decision is highly judgemental. To the extent that they remain fixed in time, then they may be considered mere "milestones," and the "decisions" become relatively automatic as the technology progresses. In reality, given the uncertainties of government and consumer behavior, the decisions are real ones because the criteria are dynamic. On the other hand, major technological changes of the nature of an alternative powerplant, which require years of gestation in the TD&P process, must be tied to long-range corporate strategy and thus somewhat insulated from yearly fluctuations.

Figure 2.1 indicates the position of Basic Research as one source of ideas for innovation. In fact most innovations enter the process at the Selection Decision from other, related markets or other firms. The disc brake, for example, became widely used on aircraft in the mid-1940's, racing cars in the mid-1950's, and European passenger cars in the early 1960's. It went through the Initial and Final Development stages in the American industry for the extensive adaptation necessary for the American market during the 1950's and early 1960's before being introduced by the American Big Three in the mid-1960's.[35] The Wankel engine was already in production in Europe when General Motors made a positive Selection Decision.

As shown in the figure, an innovation may occasionally enter the system at the Final Development Decision if it can be adapted readily from an external source. As previously discussed, the process described here does not do justice to the complexities of the innovation process or the flexibility which may or may not be available to the manufacturers. As discussed above, for example the Big Three will likely use various techniques to reduce their initial investment while testing the market during the Introduction Stage. This may change the TD&P process; for example the costly process of production engineering, i.e. the detailed establishment of the minimum cost design and manufacturing techniques may be partially postponed until after introduction. On the other hand, in the case of an innovation introduced under government mandate, such as low-damage bumpers or catalytic converters, the entire Introduction and Mature Production Stages may be drastically compressed and the innovation installed on all (or virtually all) of the vehicles marketed in the model year of introduction. This can be very costly as the ordinarily time-consuming optimization process associated with normal industry practices is compressed and introduction standards relaxed.

As indicated in Table 2.1, the nature of the risks involved at each decision determine the type of decision-making procedure used by the Big Three. The probability of failure, i.e. pure risk, is monotonically reduced through the process, but becomes small only after a successful introduction. In the earlier stages judgemental decision-making procedures incorporating the variabilities of consumer and government behavior, the importance of matching the offerings of the other firms in order to protect the firm's long-run market share, and (most importantly) the technological

uncertainties, are used. This makes it inherently difficult to forecast the firm's behavior. Only after a successful introduction do the economics become similar, in terms of risk, to that of ongoing products and thus more easily modeled (but by then government-supported R & D obviously has little impact). The Introduction Decision, where consumer response is not yet clear and the magnitude of the necessary investment is very large, is where the firm faces the decision where the dollar risk, i.e. potential impact on the firm's financial position, is greatest.

Up to this point we have discussed how a successful innovation proceeds through the system, and we have discussed the uncertainties and risks involved at each stage. The pure risk in any stage (as previously defined) is associated with the probability of failure during the stage; failure means not meeting the criteria for the positive decision at the end of the stage. The element of time is ambiguous and difficult to model. Obviously the Big Three, like other major firms, conduct periodic reviews of their portfolio of projects in each stage of the TD&P process. The continuing investment for each project must be assessed against the managers' expectation for success within some time frame. A project may drag on for years in the Initial Development Stage as incremental improvements are made, expenditures kept low, but the success criteria not achieved. Similarly, a project may fall back from the Final Development Stage due to failure of cost reduction efforts or a change in criteria due to (for example) changes in consumer tastes.

The timing and dollar investment in each stage for a successful innovation is highly variable, depending on the extent of technological change (product or process) involved in the innovation, the strength of the

incentive to make the change, and the actual manufacturing cost of the item involved. Initial Development for a major innovation will certainly never take less than several years unless the particular technology has been previously applied in very similar situations and the incentives are very strong. Final Development is likely to take several years, as this is again about the minimum, and the relatively higher expenditure rates provide an inherent incentive for a rapid completion (or a rapid determination of failure). Similar considerations apply to the Introduction Stage. The Mature Production Stage is typically more leisurely, and is often demand - rather than supply-limited. While significant expenditures are involved, they are capital investments with relatively low risk, so there is no inherent financial pressure for a rapid production buildup. Typically this stage has taken from 5 to 15 years in the past. The distinguishing feature of the Mature Production Stage, however, is the optimization of the innovation and its manufacturing processes. The ultimate extent of market penetration of the innovation may or may not approach 100% of new vehicle production; this will naturally depend on the desirability of the product relative to its costs and how it meets the requirements of the diverse segments of the market. By far the most dramatic innovation ever made by the industry, in terms of timing, was the equipment of almost all production vehicles with the catalytic converters in model year 1975, from a Final Development Stage effectively beginning in the late 1960's. This was occurred (was essentially made mandatory) as a result of the intense pressure of the Clean Air Act and the fact that the innovation was an add-on device, requiring very little modification of the remainder of the vehicle (i.e. it had a high degree of integrability).

Figure 2.1 also includes the turnover of the in-use vehicle fleet as the final stage of the overall innovation process (although not part of TD&P). An innovation has a significant aggregate impact only after enough of the new vehicles have been sold to replace a significant fraction of the in-use fleet. This process is not within the control of the Big Three, however; it is determined by the aggregate economics of the process of vehicle population turnover. It adds another five years or so to the total time from an initiation of the Initial Development stage for an innovation to its incorporation into a significant fraction of the nation's vehicle fleet. In the subsequent chapters of this report we will consider government supported R & D on alternative powerplants for the ultimate purpose of obtaining very large social benefits, from reduced aggregate air pollutant emissions and reduced fuel consumption; the time for the turnover of the in-use fleet is of obvious importance in these considerations.

2.4 Summary And Some Preliminary Conclusions

It is worthwhile at this point to review and highlight some of the points developed in this chapter which will be most germane to the subsequent discussion of government involvement in R & D on alternative automotive powerplants. We are dealing with a major industry whose unique characteristics must be carefully considered in any proposed government program to change its product technology.

First, the automotive industry exhibits many of the features associated with "mature" industries; of most significance here is the dominance of technological product change through slow evolution rather than dramatic breakthroughs. Major technological changes in such

industries are often made by invasion of new firms (or firms from other industries) willing to exploit a new technology. The barriers to entry in this industry, the riskiness which is an inherent part of changes in its products, and the ability of the Big Three to respond to external technological threats, make such an event exceeding unlikely in this case. We are, therefore, left with dealing with the present Big Three.

We have emphasized that product change in the automotive industry is a very risky business. The replacement nature of the demand for automobiles allows consumers considerable temporal leeway in their purchases, and seventy years of continuous evolution have accustomed automobile buyers to expect very attractive levels of all the important attributes of their vehicles. A major product change poorly handled invites significant loss of sales and several years of consequent economic disruption. The skills which have been developed for dealing with this demand function lie in the Big Three. Furthermore, the risks in technological change, as perceived by the Big Three, have been increased by the government intervention which has occurred to date and, given the present tempo of debate in both the Administration and the Congress, are not likely to be abated in the foreseeable future.

We have developed a very simple model of the process of automotive TD&P, consisting of a set of stages of activity and intervening decisions. Most of the "R & D" takes place in the Initial and Final Development Stages. The Introduction Stage, however, is the focal point of the entire process; it must be anticipated by previous stages, and its success makes the Mature Production Decision a relatively easy one. Its key characteristics of significant probability of failure combined with large initial investment

lead to a likely introduction strategy wherein the fixed cost of the innovation will be kept as low as possible, consistent with an acceptable probability of failure. Thus, the innovation is designed for a high degree of "integrability" so that the amount of redesign required in the automobile body and the related components is held low. Furthermore, a manufacturing process using less than optimal (long-run minimum cost) capital investment is likely to be used; the initial production will likely involve variable costs higher than the long-run optimum, and thus total product costs higher than the long-run minimum. These techniques allow the manufacturer to minimize his losses in the case of failure of the innovation to meet the market test. Only after a successful Introduction Stage will the vehicle redesign and increased investment in new process technology and specialized tools result in the most efficient product and manufacturing system combination. This has been the pattern in a number of past automotive product innovations, and will be seen to have significant implications for the likely introduction process for an alternative powerplant.

Finally, the total time-to-impact of a technological change depends on the magnitude of the technological changes, the incentives to make the change, etc., and includes the times for each stage from Initial Development through Fleet Turnover. For a major technological change, such as to an alternative powerplant, a decade, at least, and more likely two decades, would be required.

At this point we have not yet addressed the question of the social desirability of the conversion to an alternative powerplant. Assuming such desirability, however, the challenge is to design a government strategy to prod and guide these firms through what could be, if not carefully

handled, a traumatic experience for them and, due to their national economic significance, the nation as a whole.

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3. THE NATURE OF THE FEDERAL R & D DECISION

For the automobile industry, the decade of the 1970's is proving to be a period of disruption and transition. Not only has the industry already followed its most successful year ever (1973) with two of its worst years since World War II but, more importantly, the industry's relations with the Federal Government are in a state of flux. Major changes have been brought about, or are in the offing, as a result of public concern about safety, environmental pollution, and energy conservation. Many issues have been settled, but other important policy decisions affecting the industry -- such as precise emissions standards and future fuel prices -- remain unresolved. So also is the issue of the degree to which the Federal Government should participate in the process of technology development within the industry. The question of government intervention in this aspect of industry operations is difficult enough in itself -- stirring, as it does, deep waters of controversy over the proper role of government in the private market economy. The fact that this discussion arises in the context of uncertainty on so many related fronts only serves to complicate matters for those charged with planning and carrying out Federal R & D programs.

Before outlining the structure of this chapter, two issues are worth a brief discussion. First, it is important to keep in mind the distinction between government support of automotive R & D and government conduct of such R & D. Government-supported R & D may be conducted either by government organizations or by contractors, whereas government-conducted R & D is virtually always government-supported. In this report we are principally concerned with the issue of government support, i.e. the expenditure of tax

or other public revenues for advancing automotive technology. This is what we will generally mean when we refer to "Federal R & D". If the government decides to support a given technology, then the question of where the R & D should be conducted is addressed as part of the consideration of program design. The nature of the organization conducting the R & D, e.g. its incentives structure, can be very important in determining the outcome of the program, and therefore may enter into the support decision, but we will treat this as a secondary consideration.

Second, a brief note on the uniqueness of relations between the government and the automotive industry provides some perspective on the subsequent discussion. This study would never have been initiated had not the tradition of little government funding of civilian automotive R & D been a long and deep one, supported by both government and industry. The most obvious contrast is the opposite tradition of substantial support for civilian aircraft technology, a tradition strongly supported by both government, the airframe manufacturers, and the airlines. Of course the bulk of government support of aircraft R & D has been by the Defense Department in support of procurement needs, and this has had significant spin-offs into civilian aircraft technology. However, there has also been substantial direct support of civilian aircraft technology, principally by the National Aeronautics and Space Administration (NASA, and its predecessor the National Advisory Committee for Aeronautics, NACA), but also by the Federal Aviation Administration (FAA). This has even included support of general aviation (small civilian aircraft) technology. Recently NASA proposed a \$670 million, 10-year, R & D effort aimed at reducing civil-air-transport fuel requirements by 40-50%. It was received by a sympathetic Senate Committee on Aeronautical and Space Sciences,

strongly supported by the airline industry, and a NASA advisory board stated that they were unanimous that "NASA struck a proper balance between government and industry roles" in the program (although some concern had been expressed by the Office of Management and Budget on the latter issue). [37, pp. 10-13] We will not analyze the reasons for the different traditions in government-industry relations, they are complex and the market structures are very different, but we only point out the tremendous impact the traditions have on the extent and nature of analyses required to support government R & D in the two fields.

In this chapter we set the context for discussion of Federal R & D decisions in the automotive area, and suggest some broad guidelines for analysis of Federal programs on alternative powerplants. Given the nature of the ongoing debate, the discussion naturally begins with a review of the various types of government programs devoted to automotive research, and to their justification in the face of such a large and established industry. The focus is on programs to prepare new technical options for automotive propulsion, and attention is given to the various failures in the market that create a need for publicly-financed investigations. Of course, even if a new technology is developed, it still must win a place in the market, and the discussion next turns to the issue of "commercialization" as it reflects on Federal consideration of potential R & D programs. Then the critical uncertainties and their impact on the usefulness of analytical R & D selection and planning techniques are explored. Finally, the insights drawn from this review of the problem are pulled together in a brief outline of the steps that one would go through in evaluating proposed Federal activities year-by-year.

3.1 Alternative Directions for Federal Automotive R & D

There are several reasons why the Federal Government may become involved in supporting R & D programs, and as discussed in the Preface, this report is concerned with only a subset of these activities. To put the discussion in context, therefore, it is useful to begin with a brief overview of the various objectives that may be set for Federal R & D programs. Here we define four sets of objectives¹:

- to support procurement,
- to back up regulatory and policy decisions,
- to influence private industry activities, and
- to provide new options for commercial application.

In most circumstances, one or another of these objectives dominates program design and administration, although many programs seek multiple objectives and there are inevitable spillover effects, with contributions to objectives that are not explicitly stated. At one time or another, each of these objectives has been used to justify the government's automotive R & D programs. [1] In Section 2.3 a simple model of the automotive technology development and production (TD&P) process is presented, along with the preceding and subsequent stages (Basic Research and Fleet Turnover, respectively) of the more extended process of changing the in-use fleet. Corresponding to the different stages of this process -- from Basic Research through Fleet Turnover -- there are opportunities for government involvement.

¹This taxonomy of objectives is discussed in greater detail in the first report of this project. [1, Chapter 3]

Some activities can be justified as appropriate areas for Federal intervention while others cannot.

Table 3.1 summarizes the taxonomy of objectives and R & D activities developed in this section. Across the top of the table are listed the four principal objectives of programs in this area; down the left side are listed the different types of R & D that are relevant to the automobile industry. The table indicates which of the different objectives are compatible with the various types of R & D activities, and summarizes several propositions that have guided our work on this issue.¹ Let us look at each objective in turn.

3.1.1 R & D To Support Government Procurement

Over the country's history, the major portion of publicly-sponsored R & D has been a natural part of the government procurement process. Most military and space R & D is usefully viewed in this way. The Department of Defense may have a demand for a particular piece of equipment or a system

¹Once again, a more complete discussion of Federal activities -- including assessments and impact studies, and performance and emissions testing -- is included in the preliminary report. [1].

Regarding "Basic Research", the expansion of the frontiers of knowledge is a sound objective of government programs and this type of research has always been a justifiable activity in this regard. However, Basic Research is not the real issue in this study, for most research at the "basic" level is sufficiently unfocused and removed from "available technology" as to be of only partial relevance to specific applications to automotive propulsion systems. (There are a few important exceptions such as fundamental work on electrochemistry and related scientific work on storage batteries, the structural properties of ceramics, basic studies of NO_x formation, etc., but even these could not have any real impact for decades).

Table 3.1¹

DIRECTIONS FOR FEDERAL R & D EFFORTS ON AUTOMOTIVE TECHNOLOGY

TYPES OF RESEARCH	OBJECTIVES			
	Support Procurement	Data for Policy, Regulation and Public Info.	Influence on Private Efforts	Advance State-of-Art
Basic Research		Not usually relevant	Not relevant	Appropriate
Technology Development	All these types of research are appropriate to support procurement	Appropriate when information not available or credibility questioned	Limited impact on industry R & D programs	May be appropriate when options are not being explored
Initial Development		Unlikely to be appropriate		
Final Development				High cost, questionable

¹Adapted from Table 3.3 of our first report. [1]

to perform a certain function, yet the technology does not exist, or does not exist in usable form. A necessary first step in procurement is to finance the work required to solve engineering and technical problems, or even to establish the scientific basis for the function to be performed. In the automotive field, an example of this type of program is the work on the stratified charge, gas turbine, and diesel engines supported by the U.S. Army Tank-Automotive Command, for tanks, jeeps, etc.

Naturally, the spin-offs from this procurement-oriented research can be significant. Often these by-products are offered in justification for government expenditures, even when this spin-off potential does not determine the scale, composition, or longevity of the programs in question.

No one doubts that the Federal Government should be conducting programs with the objective of meeting justifiable procurement needs. All the various types of R & D activity may be involved in this process. However, this has little direct relevance to Federal R & D on alternative automotive powerplants, since government procurement needs for passenger cars and other civilian-type light duty vehicles are very small relative to the total market.

3.1.2 Research to Develop Data for Regulatory Decisions, Policy Formation, and Public Information

A separate and distinct justification for Federal R & D is the development of information to support government regulatory efforts. In taking actions that directly influence private industries or individual persons, key scientific and technical facts may be of critical importance. Without them costly mistakes are possible. Sometimes the needed knowledge does not

exist at all and the government must develop it.¹ In the case of automotive air pollution, for example, Federal agencies had to conduct research on the health effects of pollutants, and on the appropriate driving cycles and instrumentation for emissions testing. These data were needed as a basis for setting regulatory constraints. By the same token, regulatory agencies may need to develop knowledge about the feasibility of achievement of various levels of standards, or about the ramifications of expected industry responses to particular constraints.²

In other situations, the technical knowledge may exist but may not be in the public domain due to the proprietary interests of the industries involved. Federally-sponsored research can develop the data and make it publicly available. Or, research results may be available from industry sources, but their credibility may be challenged because the companies are parties to regulatory action. Without an independent R & D effort, responsible government officials may have no sources of data other than the regulated industry itself. Aside from the needs of policy analysis and regula-

¹A good example of R & D with this objective is the recently completed Climatic Impact Assessment Program (CIAP), supported by the U.S. Department of Transportation. It was designed to provide information to support U.S. policy and regulations on the performance and/or use of supersonic transports, by examining the potential impact of their emissions in the stratosphere and measures which might be taken to alleviate that impact. [38]

²One example of a situation where research of this type was lacking is the case of the sulfate-catalyst problem. Having adopted regulations that forced manufacturers to produce catalyst-equipped vehicles, the Federal Government might well have initiated a research program to investigate the full range of possible consequences of such a technology.

tory decision, the government may have reason for research programs to provide information to the public at large, often with consumer protection as the overall objective.

Thus given the regulatory responsibility of the Federal Government, and the continuing requirement for data to support policy decisions, there is need for Federal investment in R & D on topics specifically related to these functions. In meeting these responsibilities, all categories of R & D may be called for, although Basic Research is likely to be relevant only under very special conditions, and the latter stages of technology development are less likely to be justified as a public expenditure, as suggested in the table.

3.1.3 Research Intended to Influence Private Industry Efforts

The two objectives above relate to straightforward concerns of government in its role as purchaser and regulator. This third objective, however, is political in nature. It is a subtle and often unstated purpose of some Federal R & D efforts. One instance where this objective becomes relevant is in regulatory situations, where only the regulated industry itself has the data to determine if particular constraints are reasonable, or if certain advanced technological solutions are feasible. Whether based on expert internal judgement or a general resistance to change, corporations may decide not to expend funds to explore certain technical options, and there may be little that government authorities can do directly to insure that new or radically different technical options are fully evaluated.

Federal programs can have an indirect influence in this circumstance in that they may trigger a "defensive" R & D effort from industry. No com-

pany wants to get caught without the technical knowledge to defend itself against regulatory proposals based on Federal research results or news releases portraying some dramatic success. This is true particularly where the industry has argued that certain targets could not be achieved. And so a possible goal of Federal R & D is an adjunct to the regulatory process -- to goad or threaten industry to undertake parallel R & D efforts on its own, or to upgrade the priority attached to particular programs.

No doubt any substantial research activity in a new technical area will spur interest and (perhaps) a parallel effort on the part of industries that have a stake in the area in question. This is a natural aspect of the competitive process and a normal component of industry-industry relations. However, government R & D programs which explicitly or implicitly seek to apply leverage to private sector efforts, while they may generate political pressures, are not likely to have a great influence on the level and direction of industry programs on alternative automotive power systems. When such influence is exerted, it is likely to be because of the inherent value of the research results rather than the threat of a breakthrough which would compromise the industry's position.

3.1.4 Research to Advance the State-of-the-Art and Open New Options for Commercial Application

Finally, there is the objective that is the central focus of this report -- that is, Federal sponsorship of R & D explicitly to advance the state of scientific knowledge and the practical arts of engineering application, and thus to increase the number of technical options available for future consideration by private industry. This is a traditional goal of

R & D, and is an objective associated with many Federal expenditures in this area. It is the objective of much of the work supported by such agencies as the National Science Foundation, the National Institute of Health, the Department of Agriculture, EPA, the aeronautics work of NASA and the FAA, and it is often the stated goal even when other considerations are important in program justification. Even where advancement of the state-of-the-art knowledge is not a primary stated goal, most expenditures on R & D yield some by-products or "spin-offs" of increased understanding and widened technical opportunities. Most importantly for this discussion, this is now the primary goal of the automotive programs that were brought into the Energy Research and Development Administration (ERDA). [39]

One of the key issues addressed here, of course, is the extent to which Federal expenditure is justified in R & D on the product of an industry as large and experienced as automobile manufacturing, and with so large an existing in-house R & D capability. The answer to this question ultimately must come with reference to specific technologies, but there also are some general comments worth making.

3.2 The Justification for Federal Involvement in Developing New Options For Commercial Application

As in most other areas of the private economy, the traditional pattern in our society has been to leave to private industry the task of researching and developing new product lines for sale in commercial markets. So long as markets function well, this pattern is rarely questioned, and indeed the great bulk of the R & D carried out in the United States takes place quite outside the direct concern of the Federal Government. However, problems

arise when markets do not function properly -- when markets "fail", in the economics jargon. In the most general terms, this "failure" occurs when the social evaluation of the costs and benefits of a particular action are not fully reflected in the private costs and benefits to which corporations and individual consumers respond, i.e. there are "externalities" involved. Where the incentives to private behavior are judged socially undesirable or inadequate, intervention by the government, as the agent of society as a whole, may be called for to correct the imbalance.

Direct involvement in R & D is only one of the many instruments available to government to accomplish such ends, however, and it is probably one of the weaker measures as compared to regulation, taxation, and direct subsidy programs. Indeed it can be argued that most of the problems discussed in this report -- to which the Federal R & D program is directed -- could be as well or better solved by appropriate sets of taxes and charges, which would correct the private cost to correspond to the social.¹ But though this may be true in principle, it has little relevance in practice -- at least for the immediate case at hand -- for there seems little chance these measures will be utilized. The emphasis in policy with regard to the automobile seems to be on regulation of vehicle performance characteristics, and direct involvement in the process of technical development and change. As a result of these well-established patterns in U.S. policy, some level of Federal R & D on alternative automotive powerplants has become a continuing if controversial component of the Federal budget. Potentially this work could make a substantial contribution to the country's future welfare.

¹Examples would include various combinations of emissions charges, taxes on fuel consumption, etc.

It is relatively easy to find some sort of failure in most any market, and there are good arguments (discussed below) as to why the private incentives for the performance of R & D are always inadequate. There is a tendency to cite them in passing and proceed to "justify" government investment in R & D, without examining the government's other, sometimes extensive, interventions in a given market and their impact on the incentives for R & D.¹ In this section we therefore undertake an examination of the possible disparities between the social and private incentives for R & D in the automotive market, including the government interventions presently extant. We will attempt to confine ourselves to those features of the market which relate to R & D in alternative powerplants; e.g. we will not look at other alternative issues such as safety, damagability, support of road construction, etc.

3.2.1 Traditional Economic Arguments

One set of conditions that justifies government intervention in the process of technology development occurs when various "failures" arise in the performance of economic markets, even when those markets are perfectly competitive.² For example, certain types of technical developments may have the character of a "public good" where the knowledge, once developed, is not

¹Eads argues this point very strongly, with the civilian aircraft industry as a case study. [40]

²An excellent summary of these arguments is provided by Holloman, et. al. [41]

exploitable by any one firm. All competitors receive the benefits, and there is insufficient advantage to any one competitor to expend the funds to carry out the technical development. Much of basic research -- which is devoted to the increase of human knowledge rather than the development of specific technological procedures -- has this character, and it is for this reason that a great deal of basic research is justifiably carried out with some involvement of public funds. (It should be emphasized, of course, that a great deal of basic research is supported by private corporations as well.) At some level this argument holds for all markets and technologies, and might be cited to support, for example, research on less expensive washing machines. A unique feature of the automotive market, however, is its vast economic size, so that very small changes in automotive technology make very large differences in social welfare when used over the roughly one trillion miles driven annually by the American passenger car fleet. Thus the "public good" argument applies with particular quantitative strength in the automotive case.

Another circumstance that may call for government intervention arises when there are "externalities" of one type or another. An externality occurs when an economic decision-maker -- be he a supplier or consumer -- is not faced with the full costs (or does not receive the full benefits) of the actions he takes. That is, market prices fail to reflect the full range of impacts of a particular decision. A clear example is automotive air pollution, where the operating costs of an "uncontrolled" vehicle did not reflect the damage being done to others through tailpipe emissions; thus clearly justifying some sort of government intervention. In such a situation the imposition of regulatory performance standards (such as those of the Clean

Air Act) may provide an incentive to manufacturers to carry out needed R & D. On the other hand, regulatory constraints have turned out to be very crude instruments from the standpoint of spurring technological development: they have not proved to be efficient instruments for calling forth the desirable level or mix of R & D on ways to reduce the externalities. Thus a solid justification exists for the involvement of public bodies in research to find ways to reduce the external affects; this will be addressed in more detail below.

Another externality of automotive operation, though less obvious than that involved with air pollutant emissions, is that the present high level of consumption of gasoline (and all other petroleum products) exposes the nation to blackmail by the Arab oil producers. That is, there is a value to the reduction of petroleum imports that is higher than the avoided cost of the petroleum itself. Thus the price of automotive fuel is too low by (at least) a "security premium". One ramification is an underinvestment in R & D on any fuel-conserving technology, such as the interesting alternative powerplants.

Still another example of a market failure, though more controversial than the ones above, is that which occurs when the relevant private decision-maker has a degree of risk aversion which is significantly different from that of the society at large. In essence, the government is capable of spreading the risk of particular technological experiments over a very large pool of alternative activity. A private corporation, on the other hand, may be limited in its ability to diversify the risk of a large investment (say in a new technology) even if the corporation's estimate of the expected value of the investment is the same as that of the government.

Now, of course, it is argued that a variety of financial measures exist within our market system to allow a private corporation (or individual stockholders) to diversify risks of this kind, and therefore that the risk aversion of the private corporation should be no different than that of a public body. But once again these arguments depend on the efficient working of financial markets, and to the extent these markets "fail" in one way or another, the private and public perceptions of risk may be different. This will happen, for example, when the formation of various types of risk pools is retarded by various government restrictions on the market, such as are imposed by the anti-trust laws.

Thus it might very well be the case that an expensive venture on the part of Ford or General Motors may involve a degree of risk to the corporation which mitigates against its adoption, while at the same time the society as a whole could well afford to bear the risk given its capacity to spread risk over the body politic as a whole. In these circumstances there is a justification for government involvement in carrying out such experiments. In fact, on the basis of a 1969 consent decree between the automobile manufacturers and the U.S. Justice Department, the manufacturers are specifically forbidden from collaborating on R & D related to air pollution control. There is a trade-off here between the ability to form risk-bearing consortia and the need to maintain competition that is beyond the scope of this discussion. The fact remains, however, that, with ventures of the size involved in the development and introduction of an alternative powerplant, the risk as perceived by a manufacturer and its management may well be much larger than when calculated socially.

3.2.2 Problems of Market Structure

Another circumstance which also leads to a concern for government involvement in technical development concerns the structure of the automobile industry itself. All of the arguments in the previous subsection hold when the market is made up of large numbers of sellers and buyers. As discussed in Chapter 2, however, the supply of automobiles to the American market is dominated by the "Big Three," with a fringe consisting of one "independent" and a number of importers. In such a circumstance there are good reasons to suspect that the full play of competitive forces is not brought to bear. As discussed in Chapter 2, there are really two questions here: the large scale necessary for the economic mass production of motor vehicles through the extensive use of automatic machinery; and the small number of sellers that has resulted from the development of firms probably beyond the size required for these economies. The former may result in a more than optimal degree of sluggishness to technological change. The latter may reduce the degree of competition, but, on the other hand, the existence of such huge industrial complexes and their associated financial power gives opportunities for R & D that might not exist were the industry made up of much smaller units.

So therefore, on balance, it is not easy to argue whether more or less R & D on new technical options takes place under current market structure or some alternative. As discussed in Chapter 2, debate on this issue has been hot and heavy, both within the academic community (on the general issue) and among those involved in automotive issues. It is impossible to resolve this issue as it bears on government support of alternative powerplant R & D.

3.2.3 Unintended Impediments in Federal Regulation

As important as are the traditional economic arguments under competitive markets or the special circumstances in oligopolistic markets, there is in the automotive case a host of imperfections that are introduced by government regulation itself. Two areas of present government regulation are significantly reducing the incentives for R & D on alternative automotive powerplants.

Present Federal price controls hold the prices of automotive fuels well below their marginal cost. The legal price of gasoline (and all other petroleum products) is based on an "average" cost of crude oil, where the average includes imports and "new" and "released" domestic oil at prices determined by the Oil Petroleum Exporting Countries (OPEC) cartel, and "old" domestic at a much lower price, presumably related to its old "cost". The problem is that the production of domestic crude is relatively fixed, so that any gallon of crude that is not consumed results (more or less) in a gallon of crude not imported. But, because price controls hold the cost of automotive fuels well below their cost based on the cost of imported crude (i.e. their marginal cost), the savings privately received in not consuming a gallon of automotive fuel are substantially lower than the savings received by the nation as a whole in not having to import the extra unit of expensive international crude oil. This will be discussed further in the following section, but as long as petroleum price controls are continued, then (as in the case of the "security premium" discussed above), all investment in fuel-conserving technology will be undervalued in private decisions; specifically, this includes investment in R & D on alternative automotive powerplants which consume less fuel than the ICE.

The other regulatory program in this category is the Clean Air Act, which, in its structure, and its history and administration, biases investments in R & D on technology to control air pollution -- away from major technological changes (such as alternative powerplants) and towards smaller, "evolutionary" technological changes (such as those which have been implemented to date and are being considered for the foreseeable future (see Chapter 4). The history and basic structure of the Clean Air Act and its implementation were summarized in Chapter 2, and will not be repeated here; rather the impact of its key features on the incentives for alternative powerplant R & D will be addressed.

First, there has been continuing short-term uncertainty in the emissions standards. For example, as of this writing there is general agreement that the presently legislated model year 1978 standards are "too stringent" and will not remain on the books. Congress has been considering revisions to the model year 1978 standards for over a year now, and neither of the relevant Congressional committees has yet reported a bill to the floor of its respective House. The manufacturers will not know the 1978 emissions standards until well less than two years before commencement of mass production. This type of uncertainty forces the manufacturer to focus his best resources on getting his new cars into production at the legislated levels with minimal cost and disruption; that is, it shortens his time horizon.

Second, there is substantial uncertainty in the "long-run" emissions standards, and it may be the case that there will never be any stable long-term standards. For a while it appeared that the original 1976 standards would be postponed until they could be met, but even the EPA now agrees that the original NO_x standard is too stringent. No one knows what Congress will

do. In terms of overall impact on investment in alternative powerplant R & D, the effect of this long-term uncertainty is to increase the risk involved in any such investment, and thus lower the investment level. It also biases the choice of alternative powerplants toward those which can meet the most stringent standards on the books, even though such standards may well be changed.

Third, the Clean Air Act requires that (virtually) every car produced in a given year meet the same standard. This raises a major difficulty. As discussed in Chapter 2, a major technological product innovation such as an alternative powerplant, could not possibly take place in a single year. Some of the alternatives may meet the present long-term statutory (original 1976) standards, but the ICE may never be able to meet them with the "available technology", i.e. at reasonable cost penalty. Consider, then, a manufacturer who has successfully developed an alternative powerplant meeting the statutory standards, at an appropriate cost penalty, in the case where they had not yet been met by the ICE. The manufacturer could offer, initially, a few hundred thousand vehicles with his new engine, but consumers would prefer the less expensive ICE-powered vehicle with the higher emissions. The Act would have to be amended. It is reasonable to assume that some form of equipment standard would be legislated along with a schedule for the production build-up, in a highly political decision process. Thus a manufacturer, looking ahead to this possibility, sees great uncertainty and risk. In fact, the annual change of emission standards was taken from the industry's traditional annual model change. But this tradition has been based on a slow, evolutionary, development of the automobile, with many small year-to-year changes (mostly in external styling) that can be introduced simultaneously

across a full model line. The Clean Air Act therefore encourages exactly the sort of evolutionary change that is the industry's natural bent.

Fourth, and finally, there is an inherent difficulty in dealing with presently unregulated emissions. For example the diesel has special emissions problems (e.g. particulates) that might create problems if the engine were introduced in mass-scale passenger use. As yet the emissions standards to be applied to these emissions have not been determined by Federal regulatory authorities, and so long as this uncertainty remains it is not in the interest of any manufacturer to spend substantial sums of money on the development or introduction of the diesel engine. Now it is possible that regulatory constraints on diesel emissions ultimately will be set at a level that allows the diesel to function as a passenger car engine. But in the meantime the risks in the development of this engine are significantly increased. Furthermore, it is very likely, due to the press of shorter-term matters, EPA would not conduct the necessary impact studies and lengthy regulation formulation and adoption procedures for setting a particulate emissions standard until diesel use became widespread. Thus there may be a fundamental dilemma which will have an inhibiting impact on diesel development efforts.

In summary the Clean Air Act and its history and administration, as the result of Congress' desire for haste in reducing air pollution levels, has significantly biased the industry away from major technological changes such as some of the potential alternative powerplants, in the effort to reduce automotive emissions. The principal source of this bias is the increased risk it has added to such developments. These added risks have been imposed on the manufacturers by society but they are not risks as perceived by

society. Again there is a significant disparity between the social and private incentives to the development of alternative powerplants.

3.2.4 Some Conclusions Based on Analysis of Social/Private Disparities

In summary, it is very likely, for the reasons described above, that the automotive industry will under-invest in alternative powerplant R & D, relative to the level which would be socially desirable. This provides a solid but very general justification for government support of alternative powerplant R & D. However, what guidance does this provide us in our analysis of project choice or program design in this area? Unfortunately, not very much. Due to the nature of the disparities between the social and private incentives, it is very difficult to look for R & D projects which would be economically justifiable from a social basis but not a private one and then confine government expenditures to them. Evaluation of risky R & D projects is difficult enough (as will be discussed in Section 3.4 below); here we would be evaluating (among other things), differences in risk.

We can draw the very general conclusion that the government is justified in supporting this type of work -- but we cannot apply this to specific projects. All we can say is that the government should be sympathetic to proposals in this area. But, in negotiating contracts with industry it should be tough enough that the firm does invest what it considers an economically justifiable amount, so that the government is not merely replacing industry dollars with the taxpayers'. The boundary, however, will be very difficult to determine.

3.3 Commercialization of a New Powerplant

Whatever the purported social advantages of a new automotive propulsion technology, and even assuming technical R & D goals can be met, there remains the question of the adoption of the new approach in commercial markets. In general, the government does not directly decide the technical details of automotive design (though it may regulate vehicle attributes), and therefore there may be reasons why the manufacturers might not be interested in carrying a new technology through the Final Development and Introduction Stages, even though it might look attractive in a social benefit-cost calculation. This might happen for any of several reasons, and often they would be the same reasons (argued above) why the manufacturer might not carry out the R & D in the first place. Market prices might not reflect the presumed social costs and benefits of particular inputs and outputs -- as happens with pollutant emissions, or as would be the case if the fuel price failed to reflect the true social cost of imported oil. The desire on the part of the three major domestic manufacturers to maintain established patterns of competition, market shares, and industrial structure may mitigate against rapid change -- particularly if the financial risks are significant. Or, there may be uncertainties or other effects in government regulations that compound the risks for the corporations of a particular technical innovation.

In short, there may be a divergence between the social and private economic calculations in the latter stages of the TD&P process even if a socially beneficial alternative powerplant technology exists, perhaps as a result of a Federal R & D effort. Moreover, this divergence need not originate only in some conventional market "failure": it may be that the social evaluation is inconsistent with observed consumer tastes. For example, it

may be argued that the average motorist's implicit discount rate is too high (or his calculation horizon too short) and that he therefore makes an improper tradeoff between initial cost and fuel economy.

But whatever the reason for the suspected public-private divergence, this issue of commercial viability deserves careful attention in both the selection and design of Federal R & D programs. To anticipate our principal point: it is clear that a socially beneficial technology which does not meet private market criteria (including government interventions extant) at the time of the Introduction Decision, will only be introduced if a new government intervention takes place at that time (such as an equipment standard or a direct subsidy to purchasers).

3.3.1 Two Complicating Issues

Unfortunately for the analyst and planner, however, all discussion of the commercialization of new technologies is inevitable tangled in two unresolved issues of Federal policy:

- 1) To what extent is the Federal Government going to intervene in the automobile market by additional regulatory or fiscal schemes, and to what extent is the automotive market going to be allowed to operate on its own at existing market prices?
- 2) What trajectory of market fuel prices is the government going to set over the decades to come, considering the concern with import dependence, the need to manage the long-term energy balance of the country, and related issues of social equity and fiscal balance that are tied to the fuel price decisions?

The answers to these questions will be worked out only over many years, and they involve social and political issues far beyond the jurisdiction of the

public agencies concerned with the development and demonstration of new technical options. Nonetheless, judgements about the likely outcomes in these areas have critical relevance to the discussion of appropriate and efficient government technical programs.

Assuming for the sake of argument that the industry manufactures and sells only what the public wants to buy,¹ the issue of government intervention can be stated in terms of the degree to which consumer sovereignty is to be rejected in this market. That is, to what extent are motorists going to be allowed to buy what they individually want in the way of an automobile?

Naturally, in many cases where the consumer's decisions can injure others -- through pollutant emissions, inadequate brakes, etc. -- regulations already exist to prevent the sale of a vehicle without the appropriate devices, even if the motorist prefers it. The exact standards may be controversial, but the principle of government regulation in such cases is generally accepted. In a more limited set of circumstances, government regulations have been adopted which imply rejection of the consumer's choice when only his own convenience and safety are involved. Mandatory seat-belt-ignition interlocks were an example of such a denial of the general principle of consumer sovereignty, and the Congress' overturning of the National Highway and Traffic Safety Administration's regulations in this area indicate that such regulations are not readily tolerated by the public. There are, of

¹At first glance this may seem to be mere tautology, but it can be argued that consumer "wants" are not independent of industry advertising campaigns and that, at any rate, the domestic industry is so dominated by three firms that the consumer has little choice in the matter (an argument that is dampened by the continuing availability of a variety of imports), as discussed in Chapter 2.

course, a host of less dramatic (and lasting) examples of government intervention in consumer choice -- most often justified by the lack of information on the consumer's part (if justified at all).

The issue at hand in this case is whether restrictions will be placed on the fuel consumption characteristics of the vehicles available to be purchased, or on the particular propulsion technology to be used. The importance of this question can be seen by looking at the issue of alternative powerplant commercialization first under the assumption that no new restrictions are to be placed on vehicle design or fuel performance.¹ To be "commercial", a new technology must satisfy something like the following definition:

Given: 1) the market prices of inputs to manufacturing and maintenance, 2) the market price of fuel and 3) present government interventions in the automotive market; the technology must be available at a cost that allows the manufacturer to make a normal rate of return (or maintain his traditional market share) in its manufacture and sale.

This definition, of course, implies that the technology must be preferable or at least equal to alternative approaches for a substantial fraction of the buying public. In the current circumstance, the relevant competition is the ICE.

Thus the crucial challenge for any new automotive propulsion technology, assuming the market is to be allowed to work without new restrictions, is to provide manufacturers with an economic rate of return at least equal to that of the contemporary ICE. And since the distinguishing characteristic of most of today's leading contenders is superior fuel economy (while meeting legis-

¹Or at least that any new restrictions do not rule out one engine or another.

lated emissions standards), the challenge is to provide a fuel-economy/initial-cost combination that is more attractive than that provided by the ICE (all other vehicle attributes held equal; i.e. drivability, maintenance costs, etc.)

3.3.2 What Fuel Price?

Unhappily, this statement of the commercialization issue leads one straight into the second of the two Federal policy questions laid out above: what is going to be the market price of fuel at which this tradeoff will be calculated? The country faces a complex, continuing choice in setting domestic fuel prices. On the one hand, there are two broad policy problems that ultimately revolve around the U.S. domestic fuel price. First, a major medium-term national objective (say, over the next 10 years) is to achieve an acceptable degree of freedom from dependence on imports of foreign oil. The most important single variable in determining oil imports is the domestic oil price. Second, all the world's economies face the ultimate decline in world oil production -- an event that is generally predicted to begin some time in the next 25 to 35 years. In this circumstance, the U.S. (along with the rest of the world) faces a transition to other sources of energy -- all of which are far more expensive than conventional oil and gas in many uses. One of the key policy variables that can be used to minimize the social cost of this transition is the trajectory of the domestic price of energy over the next 20 years. Both considerations argue for high oil prices now.

On the other hand, there is strong resistance to high oil prices on grounds of income distribution, equity, and anti-inflation policy. As the recent national debate over oil price decontrol shows, the political forces

are very strong on both sides of the price issue. The outcome of the process is impossible to predict with any accuracy, particularly considering the uncertainty regarding the strength and the behavior of the international oil cartel.¹ Yet the outcome is of critical importance to any calculation of the commercial viability of several of the proposed new propulsion technologies.

3.3.3 What Regulatory Policy?

Of course it is possible to make a radically different assumption about the future level of government regulation of the automobile industry than that made in the above definition of "commercial". One can hypothesize that, were it developed, a more fuel-efficient propulsion system would be imposed on the motorist by mandate regardless of the patterns of consumer demand. There are examples on both sides of the ledger regarding this prospect. On the one hand, legislation setting fuel economy targets now appears near adoption. [2] On the other hand, there are obvious changes to save energy that have not been seriously suggested, no doubt because of an unwillingness on the part of public officials to defy clearly revealed consumer preferences. For example, the U.S. could save many thousands of barrels of petroleum per day by mandating standard transmissions (rather than automatic) and forbidding the air conditioning of vehicles. Similar gains would accompany simple restrictions on horsepower and weight. These steps seem unlikely to be taken, however.

¹At this writing the Energy Policy and Conservation Act, which would extend crude oil price controls, has come out of conference committee [2] but may be vetoed by the President. Even if signed, however, it is not clear that the ultimate decontrol of oil prices contained therein would be permitted to occur.

The implication of this discussion for R & D planning seems clear:

Although it is possible that selective subsidy and enforcement schemes may be used to force the adoption of a technology that is otherwise less attractive than the ICE to the manufacturers or the public, it is unwise to base R & D decisions on the assumption that such help will be available. To assume otherwise is to invite two types of error in the planning and design of R & D programs:

- 1) Bias in Technology Choice. It is possible to divert funds to technical approaches that will not be attractive to the consumer, or perhaps to the manufacturer, and to carry forward expensive "white elephants" which may have positive benefit-cost ratios but which no one wants (and the government is unwilling to impose) for reasons of shortcomings in cost, or non-pecuniary attributes such as performance or range. As a result, other approaches with greater promise for actual market introduction may be slighted.
- 2) Misplacement of Priorities in R & D Program Design. Program managers may lose sight of the fact that new technologies must pass successfully through the industry TD&P process described in Chapter 2 if they are to achieve large-scale market use. As a result, they may underestimate the importance of product cost control in the Final Development process, and design R & D programs that produce technical successes which ultimately are doomed to failure commercially. That is, without a continuing focus on the harsh discipline of an ultimate market test, improper incentives may be given to those carrying out the work.

These arguments have very important implications for Federal R & D planning:

1) that active industry interest in a technology (preferably evidenced by a willingness to commit some funds to its development) should be considered a decided plus in that technology's favor, and 2) that a year-by-year reassessment is required not only of the technological progress of Federal R & D programs, but of the proper assumptions that should be made about likely

prices and apparent directions of government regulatory policy.

3.4 Planning R & D in the Alternative Automotive Powerplant Case

Given the foregoing arguments the dilemma is clear. Federal R & D is well justified in theory and offers the possibility of making a significant contribution to lower fuel costs, total vehicle operating costs and air pollutant emissions over future decades. On the other hand, the character of the automotive market makes it possible that substantial Federal expenditures might contribute little to technology that actually sees the road. The task of planning and analysis activities in such a circumstance is to sort the good programs from the bad insofar as one can, and it is important to enter the more detailed discussions to follow with a realistic impression of what is, in fact, possible. The problem is dominated by uncertainties, and no standard analytical method offers an easy, or even a very good, solution to the analysis problem.

3.4.1 Critical Uncertainties

In the previous discussion, many of the uncertainties that characterize this problem were alluded to. They may be briefly summarized as follows:

- * Technical uncertainty regarding the likely results of R & D (ordinarily the crucial uncertainty in R & D programs).
- * Uncertainty about consumer tastes: What vehicle attributes will prove attractive to motorists ten to twenty years in the future?
- * Unresolved aspects of Federal air pollution regulation -- especially the ultimate NO_x standard.

- * Uncertainty about the degree to which additional government regulation will be imposed on the automobile, perhaps mandatory fuel consumption standards, or even design details.
- * Uncertainty about the market fuel prices that will prevail over the next two decades, and about the likely social value of fuel conservation.
- * Lack of specific guidance about the objectives of social policy in the automotive area, and about the tradeoffs among objectives (e.g. cost vs. emissions)
- * Difficulty of assessing what industry efforts will be in the absence of Federal involvement. (Does Federal expenditure only substitute for activities industry would soon carry out on its own?)
- * Uncertainty about the likely industry response to a socially viable new propulsion technology. (How seriously is one to take the arguments about industry resistance to switching away from the ICE due to organizational inertia, desire to preserve existing patterns of competition, etc.?)

None of these uncertainties is likely to be removed in the near future.

3.4.2 The Importance of Small Improvements

Another consideration that plays a role in studies of Federal expenditure is the sheer size of the automotive market. As argued earlier, any radically different propulsion system must win in competition with the ICE. Suppose there is an alternative technology that offers a relatively small gain over the baseline ICE technology, say in fuel economy. Further suppose that the industry is not seriously considering this technology (so that one could argue it will not be available if the Federal Government does not support R & D on it) and that the technology has a reasonable chance of being commercialized if government programs are successful. Then it is almost certain that an evaluation of the returns from Federal expenditure on R & D

will show a high benefit-cost ratio.

This point can be shown in a simple numerical example. Suppose the Federal program has a chance of leading to a new engine that will beat the ICE so that vehicles using the engine would have an advantage of one mile per gallon over the period 1985 to 2005, and suppose that ICE technology would (in the absence of the Federally-developed technology) be getting 25 miles per gallon over that period. It is reasonable to assume that during each year of the period there will be at least one hundred million vehicles on the road, each driving an average of at least 10,000 miles per year. Finally, suppose that the new engine can achieve this modest improvement in fuel economy with exactly the same emissions characteristics and initial cost as the competitor or "baseline" ICE, and let the price of gasoline in real 1975 dollars be \$1 per gallon over this 20-year period, so that the ICE technology will involve a fuel cost of 4¢/mile. The results are the following.

The increase in one mile per gallon achieved by the new technology will cut this cost by approximately 0.2¢/mile -- a saving of \$20 per year for the average vehicle. Given 100 million vehicles, all of which are assumed to shift to the new technology, this would involve a saving of \$2 billion per year in fuel, or \$40 billion over the 20-year period. The present value in 1975 of such a saving at a discount rate of 10% is in the neighborhood of \$5 billion.

Thus, such a huge market creates a condition where benefit-cost calculations will justify Federal expenditure over and above industry efforts even if the probability of technical success is relatively low, and even if there is only a partial chance that technical success will lead to mass commercialization. For example, if we suppose there is only a one-in-ten chance

of technical success and a one-in-two chance of commercialization given technical success, this still leads to a present value of over \$200 million in benefits for a government program that would achieve the results postulated.

3.4.3 Insights from Other Analytic Methods

Of course R & D decisions are being made continuously in both industry and government, and in many cases some attempt is made to back up decisions with rational analysis. Though few areas of Federal concern would involve all the special circumstances outlined above, experience in other areas does offer ideas about possible avenues of approach, and provide insight into the problems of analysis in this area. Three approaches are worth a brief summary: economic return calculations, scoring models, and decision analysis models.

Economic Return Models - For any given level of investment in an R & D project, economic return models attempt to calculate an associated measure of expected net benefit, usually stated in dollars. In a broad sense any R & D investment decision is based on an economic return model -- the trading of resources of one kind or at one time for something else inherently involves at least implicit relative values of things, and dollars are as good a common denominator as any other. Economic return models can be as complicated or as simple as is necessary or desirable in a given instance and the two other analytical techniques discussed below can be regarded as specialized economic return models which attempt to deal in detail with one or another of the difficult features of an expected net benefit calculation. Given a set of net benefit calculations, projects are ranked in order of benefit-cost ratios. Under ideal circumstances all projects with benefit-

cost ratios greater than one are funded; under capital rationing the cut-off benefit-cost ratio may be higher.

A good economic return calculation requires a complete set of costs and benefits of all the possible outcomes of a project, their distribution over time, and the probabilities of their occurrence. Simpler calculations may use judgemental estimates of probabilities. A major problem in applying such a model to the government R & D project selection considered here is in devising a procedure for weighing up the relevant powerplant attributes and combining them into a single measure of benefit. To the extent that such benefit functions are available, and widely accepted as embodying the appropriate tradeoffs among social objectives, then this type of calculation can be an important component of an R & D planning procedure, even in a simple form.

In fact, given all the uncertainties discussed in Subsection 3.4.1, little more than crude economic return calculations will be possible. Furthermore, given the massive size of the automotive market, as discussed in Subsection 3.4.2, such calculations for alternative powerplants will very likely give benefit-cost ratios greater than one.

Scoring Models - As the name implies, this approach involves the assignment of an overall "score" to each R & D project based upon judgements about its likely contribution to each of a set of objectives that the R & D program is trying to attain. In the automotive powerplant case, for example, the set of desired attributes would be listed, and a relative weighting factor given to each. For example, efficiency might be given a weight of unity; emissions, 0.5; initial cost, 0.38; multi-fuel capability, 0.76; etc. Obviously these weights would be equivalent to judgemental estimates of the relative

social values of each attribute -- so the scoring model is an attempt to deal with the difficulty of a lack of such prices by using explicit judgemental estimates.

Next, each powerplant would be judged on its potential attractiveness in terms of each attribute. These scores would usually be obtained from expert judgements, stated in a range of zero to one. Each score is multiplied by that attribute's weight, and a total score obtained by summing these products for each powerplant. The total score might then be used for a ranking of the technologies as to their relative attractiveness for funding.¹

Obviously, there are a number of problems with this procedure. First, a linear weighting of attribute subscores implies indifference between a vehicle with high cost and low emissions and one with low cost and high emissions. Though some of the non-linearity of these trade-off functions can be incorporated implicitly in the judgemental subscores, the method tends to gloss over the complex issue in practice and could, if not carefully applied, assign a high score to a technology possessing one or more fatal flaws.

A second criticism concerns the realism of the approach, for there are important factors that are not considered at all. The most obvious are the three interrelated aspects of project uncertainty: 1) probability of failure (i.e. not meeting targeted R & D goals), 2) overall project cost, and 3) expected time to projected completion. Project cost is especially difficult to incorporate in a simple scoring model, but is obviously an important decision variable. The probability of failure should influence the evaluation of a project, as should the fact that the risk can be changed by altering

¹In [42] the scoring method is actually applied to a limited set of automotive powerplants. See [43, 44] for other discussions and examples of the technique.

the funding level. Similarly, the time to project completion can be varied, and is important in comparing competing alternatives.

A final problem with the scoring approach is that it provides no justification for any specific level of funding on a given technology, or even a guide as to whether funding is justified at all. It is difficult to provide such budget justification, but this aspect of the evaluation must be viewed as a highly desirable component of any project selection model nonetheless. Most other models implicitly consider both costs and benefits in the selection decision.

Decision Analysis Models - The first two methods discussed here generally either treat uncertainty in a very primitive manner or give it no explicit consideration whatsoever. Yet uncertainty is the heart of the issue here, as noted above. Decision Analysis models recognize this role, and concentrate on explicit handling of uncertainty and risk at each stage of the R & D process.

A full application of the decision analysis approach would require that the entire R & D process from initial funding through production and market penetration be broken up into "decision points" and "chance events". These are then displayed as nodes in a tree structure in such a way that all possible combinations of events are shown. Probabilities for each of the chance events must be established a priori, though sensitivity analysis of the highest value path will indicate a range into which each probability can fall without altering the desired first decision. This technique identifies the alternative with largest expected net benefit, and also gives the probability distribution of outcomes so that the project risk can be evaluated.

Naturally, the analysis can be made very rich in detail: with the

addition of more steps, more branches, and representations of multiple attributes.

A review of present industry and government project selection methods does not reveal heavy dependence on these formal models. Various surveys of industry R & D project selection practices have reached a near-unanimous conclusion on this score.¹ For the early, risky stages of R & D which we are discussing, there is little or no utilization of the complex selection methodologies commonly proposed in the literature. Quantitative evaluation of the ultimate payoff, if performed at all, is based upon simple economic calculations, and is usually just one of a host of other factors which are considered in the final decision.

The reasons for the lack of widespread use of complex analytic project selection models are familiar. Executives complain that the models do not take all the important factors into account, that they are inadequate in their treatment of the multiple objectives for which a real organization undertakes R & D, that they are unrealistic in their treatment of uncertainty and often do not even take into account the increased probability of success associated with an increased level of effort. Finally, many models are condemned as being too complex to understand and trust fully, and as requiring more data than are commonly available.

How then does an industry or government agency traditionally select R & D projects in the Initial Development Stage? Essentially, it seems that this decision is made based upon a number of qualitative factors and a few

¹For example, see [45-49].

estimated economic criteria; these are evaluated judgementally, often by some form of project selection committee. Though studies have been done which list many of the common selection criteria used,¹ there are no satisfying descriptions of exactly how an organization's decision-makers actually evaluate the factors to arrive at a final decision. In the Final Development Stage the situation is generally similar, but since the degree of uncertainty is lower, quantitative models are used more often.²

3.4.4 What to Expect from Analysis of the R & D Decision

In summary, though the ingredients of the R & D decision are clear, there is no standard easy or really useful method for putting them together into an analysis for program planning and control. This is not to argue that quantitative analysis is not needed or useful. Indeed, the size and importance of the Federal programs on energy R & D are sufficiently great that some form of rational analysis seems essential. But whatever that analysis is, it will have to be constructed from several of the various approaches outlined above (and more), and even at its best it will have to be tempered by expert judgement on issues that cannot be considered explicitly in the analysis. Moreover, the ingredients of the analysis will change from case to case, because the nature of the key problems of the various alternative powerplants differs so greatly (e.g. initial cost for the Stirling, cost and emissions for the diesel, cost and range for the electric, etc.)

¹See [45] for a description of this process.

²The model of automotive ID&P discussed in Chapter 2 reflects these considerations.

Bearing these insights in mind, and keeping an eye on the special characteristics of the automotive case, we may turn to discussion of methods for developing information for decisions on the magnitude and composition of Federal programs in the automotive powerplants area.

3.5 Steps in an Analysis of R & D Choice

3.5.1 Description and Measurement of R & D Objectives

The first step in devising a framework for R & D planning is the definition of research objectives and the following set is relevant for work on automotive powerplant technology:

- * environment, primarily air pollutant emissions;
- * energy consumption, primarily vehicle fuel;
- * safety;
- * economy, primarily the first-cost of automobiles, and;
- * vehicle performance and driveability.

These areas are interrelated and typically involve complex tradeoffs. Although all five of these vehicle attributes are relevant to R & D project choice, it is convenient to treat them differently for analytical purposes, and to give more emphasis to some than to others. Clearly it is necessary to simplify these objectives so that the resulting analytical framework is as simple as possible. Let us look at each in turn.

Environment - Of the various attributes, the objectives for emissions are the most clear. Congress has passed emission standards (.41/3.4/.40 g/mi of HC/CO/NO_x) which presumably represent ultimate goals for vehicle

emissions. What is less clear is the degree to which cost and fuel economy objectives may be compromised to meet these emission goals. Historically, the deadline for attainment of the standards has been extended because they could not be met with "available technology" -- presumably with the implicit assumption of "at reasonable cost". Currently, there is pressure to relax emissions standards in order to gain increased fuel economy as well as some debate on whether the original NO_x standards were set correctly.

It is beyond the scope of this report to attempt to evaluate these tradeoffs. As a practical matter, we expect emissions standards similar to those now on the books to hold for the foreseeable future, though the numbers and deadlines may change somewhat. Furthermore, we expect that those standards will be met, at least by the ICE, within the time frame of the R & D projects we are considering.

For purposes of a simplified analysis of R & D potential, therefore, the environmental objective can be treated as a constraint: either a propulsion technology meets the legislated standard (or some expected modification of it) or it does not. If a particular engine is far better than the standards, then note needs to be made of that fact, and this consideration included in the general judgemental information about a particular prospect. The advantages of performance well within emissions standards does not seem important enough (particularly considering our ignorance about the marginal benefits of further emissions reductions at these low levels) to justify a complex effort to quantify the advantages to be attributed to an extra-clean engine; a few simple quantitative estimates can be useful, however.

By the same token, it is reasonable to expect that any engine that does not come close to meeting these "ultimate" emissions standards will probably

not be brought to large-scale commercial use. If there are compelling reasons to pursue a technology that offers no hope of meeting standards, the fact of its environmental disability should, once again, be carried along as part of the accompanying judgemental data. However, it is not worth the effort of calculating the emissions-economy tradeoffs -- at least not for the R & D choice at issue here.

Economy and Energy Consumption - Economy in vehicle manufacturing and maintenance is a clear objective of Federal R & D policy. Apart from a general concern with the efficient use of resources, Federal authorities must worry about cost, else a propulsion system with other desirable attributes turn out to be too expensive to capture a significant share of the passenger car market. The relevant measure of these costs (leaving fuel consumption aside for the moment) is the total "life-cycle cost" of a vehicle, including the first cost and the discounted stream of maintenance, repair, and replacement expenditures -- and of course fuel.

Fuel consumption is a complex matter, for not only is fuel expenditure a part of life-cycle cost, broadly defined, but it is the object of a stated Federal policy of energy conservation and reduction of oil imports. The conventional way of handling the additional value that may be ascribed to lowered fuel consumption is by computing a "shadow" or "accounting" cost of motor fuel which purports to reflect the true social cost of its use. This "social premium" would include the "security premium" as well as the difference between the market price and marginal cost under government regulations extant. With the addition of a premium for social values not reflected in current (or expected) market prices, the concern with overall capital and maintenance cost and fuel expenditure can be lumped into a single life-cycle

cost by using common interest rate and mileage assumptions.¹

Safety, and Performance and Driveability - Safety is regulated under Federal laws, and is little affected by powerplant choices. Therefore, it does not play an important role in the choices studied here. If an important issue does arise (such as a system posing special hazards) this fact can be carried along in an analysis as accompanying judgemental information. Of course, any system that is truly more dangerous than the general run of vehicles will be ruled out under the current legislation and administrative practice (as well as the usual consumer concerns, to the extent that consumers are aware of the problem).

The attributes of performance and driveability present a more complex problem. For propulsion systems that have similar operating characteristics, it is reasonable to assume that market forces will dictate that for any category of vehicle (e.g. general purpose vs. urban travel only) the performance and driveability will be very similar. In this case, once again, it is not worthwhile to calculate a complex expression for any small differences that remain.²

As noted earlier, difficulty arises with the electric vehicle, which will have range limitations. Once again, however, for purposes of studying R & D choice, there is not a compelling reason to try to develop a common measure that takes this factor into account, along with life-cycle cost.

¹Here, of course, implicit assumptions are being made. Motorists trade off among vehicle types depending on their expected use patterns, and thus the car with lower fuel economy, other things equal, can be expected to travel fewer miles than one with greater economy. For these rough calculations to guide R & D decisions, these influences are small.

²This assumes that fueling stations are equally available for all sources -- a condition that does not now hold for the diesel.

The fact that this limitation exists is crucial information for determining market potential. In presentations of the social benefits and costs, however, this factor is best introduced as a second attribute (to be quantified as far as possible) to be entered into final R & D planning along with other judgemental data.

Summary - There are several objectives of Federal programs to bring about technical improvement in the automotive propulsion area, and although it is possible in principle to construct detailed tradeoffs among the various vehicle attributes in order to construct an overall measure of merit, it is clear that the necessary data and social evaluations do not exist at the present time. Therefore, any evaluation of alternative technical developments is of necessity going to have to be carried out in terms of a vector of vehicle attributes, with primary emphasis put on the attribute of life-cycle cost. Thus in subsequent discussion we focus on the following definition of the principal objective of the Federal R & D program:

Reduce life-cycle cost with inputs valued in social terms (for the social analysis) or in market prices (for the private market analysis), while meeting legislatively established environmental standards.

It should be explicitly noted that in general market prices will suffice for the social analysis except, obviously, in the case of fuel.

Safety, low noise, reduced range, and other attributes of alternative powerplants can be treated as side issues which are weighed judgementally and considered on a case-by-case basis as appropriate. The same will be true of environmental benefits in the case of technologies that offer special advantages as compared with the internal combustion engine, which is likely to be the source of the definition of this environmental standard.

Given such a statement of objectives, which hopefully is sufficiently simple to allow actual calculations to be made, one can proceed to analysis of individual programs.

3.5.2 Analysis of the Potential of Individual Technical Options

The next step in the analysis of a Federal R & D program is to evaluate the likely benefits and costs of a given program. Several types of studies may be called for to accomplish this.

The State of Technology: Barriers and Targets - The natural first step in evaluating a potential R & D opportunity is to prepare data on the key barriers that have prevented the technology from entering into mass passenger car use in the past, and to establish reasonable targets for key vehicle attributes in the future. For purposes of analysis, more than one target may be chosen for a particular attribute. The study of R & D programs needs to consider a range of possible outcomes, and usually there is no single quantitative achievement which marks the boundary between failure and success.

Review of Existing Programs - What programs of research on the technology have been carried out in the past both in government and in industry, and what programs are underway currently? In reviewing a potential R & D investment it is important to understand as clearly as possible what is being done now in industry in relation to the barriers identified earlier, and why it is being done. Also, to the extent possible, it is useful to have information on the targets for achievement that are seen as reasonable by researchers who are engaged in active work on a particular technical option. Here, of course, different attributes will be relevant for different technologies. Historical data will be important as well, especially as it concerns the rate

of progress of the technology and the success or failure of previous R & D efforts. If there have been high incentives to develop a particular technology (for some other use) in the past, then one must question how much further progress can be made.

Evaluation of the Probability of Meeting Target Attributes with Different R & D Programs - Naturally, one of the key uncertainties in any R & D program is whether technical goals can be met, and in the consideration of government intervention in R & D in this industry, this issue is raised both for the Federal program itself (perhaps with companion industry efforts) and for a world in which industry efforts proceed as they will without government intervention. It is important to look at both sides of this question, for often the issue at hand is not government investment versus no investment whatsoever, but a government program to supplement or expand the existing level of effort on the basis that the probability of meeting technical targets is increased by raising the total level of resource input.

Often another component of such evaluations is to state the length of time over which such probability estimates are presumed to hold. An investment program at one level may only have a one-in-ten chance of producing a particular result by a particular time in the future; the same level of expenditure carried over a longer period of time probably has somewhat larger chances of ultimately succeeding. Or, with an input of two or three times the presumed resources, the same probability of success might be estimated for an earlier date. It is essentially the probability of technical success (by a given date, say) as a function of expenditure rate that determines the "maximum effective expenditure rate", i.e. the rate at which increases in expenditure rate no longer produce significant increases in probability of

success.

For the analyses conducted here, and very likely for most studies of Federal R & D with regard to the automobile, estimates of the probability of achieving the prescribed result should be stated in terms of some target year, say 1985 or 1990. Periods much shorter than 10-15 years are usually not reasonable for evaluating likely R & D results on major changes in technology. On the other hand much longer time horizons are less interesting for evaluations of fossil fuel powered vehicles. For electric vehicles the longer time horizons are of course relevant.

It is well known, however, that any judgemental estimates of probabilities, such as those discussed here, are uncertain at best and potentially misleading in their quantification (see [50] for a review of the subject). Even the carefully pooled judgements of experts, as in the Delphi technique, may not be very accurate -- there is of course simply no way to tell.

Price Forecasts - As discussed earlier, another key uncertainty affecting evaluations of technologies with alternative attributes is that the relevant prices of inputs to personal transportation are not known for the longer term future. For analysis purposes two types of forecasts must be made: a forecast of the market price that will exist over the next 20 to 25 years, and a companion estimate of any social premium or shadow price that should be used in the event the market price is assumed to fail to reflect the true social cost of fuel resources.

Baseline Forecasts - Any alternative must be superior to the ICE; any net benefits of an alternative must be calculated relative to continued use of the ICE. It is therefore necessary to forecast the relevant attributes of the ICE. In particular its efficiency is most important; its cost is not

likely to change as significantly. Both are very dependent on future emissions standards imposed by the government, standards which the R & D planner must view as uncertain.

Net Benefit Calculations - Given a quantitative statement of possible targets for alternative R & D programs, using the judgemental estimates of the probability that various programs can succeed, and assuming the price forecasts stressed above, the key step in any evaluation of a potential technology is the calculation of the likely net benefits of expenditure on the various stages of its development and introduction into the automobile market. Presumably different levels of government expenditure, in addition to existing industry efforts, will increase the probability that certain technical targets will be met, and the meeting of different targets yields a higher chance that the particular technology will actually penetrate some significant segment of the market. Associated with this displacement of the baseline internal combustion engine will be some set of net benefits to the society.

The key issue at this point is whether, given reasonable technical judgements about the likely results of R & D programs, the Federal expenditure appears to offer substantial benefits for the cost involved. As suggested above, one cannot expect a very accurate calculation at this stage. Such an evaluation of the expected return to R & D investment can, at best, only serve as a way to weed out the obviously weak candidates, and to clearly mark those investments which are unlikely to prove economically or environmentally advantageous.

Commercialization - Given that the rough calculations described above yield a positive net benefit to government investments when evaluated at

market prices, or at shadow prices as appropriate, the next question that must be asked is whether there are special barriers to implementation of the technology. The first place to look is in the benefit-cost calculation itself: at what points were prices or other parameters used for the social calculation which differed from values observed in the marketplace (such as fuel prices) or from values implicit in industry or consumer behavior (such as discount rate)? Each discrepancy represents a possible barrier to commercialization. Next a careful review of industry arguments and choices is obviously important. Why is the industry not pursuing the particular technology? Is it because of basic disagreements about the probabilities of success? Is it due to some market failure of the types discussed earlier? In particular, is the industry's lack of interest affected by some other aspect of Federal regulation? Or, is it simply a matter that the industry sees no particular financial advantage in transition to a different powerplant?

The answers to these questions should help pinpoint barriers to implementation or commercialization of a new technology, whether these barriers exist in the structure of consumer demand, in the clear interests of the automobile manufacturers, or in some other structural aspect of the automotive market. In the early stages of R & D on some new technology, these considerations might not weigh too heavily. But in the latter stages, as the development approaches the various steps in final development, and the costs of R & D necessarily rise significantly, these issues of industry resistance or lack of interest -- and a clear understanding of why industry is not enthusiastic -- become critically important. Once again referring to the discussion earlier, it is always possible to assume that consumer or industry resistance will be overcome by direct government intervention in the Intro-

duction Stage itself, but this does not seem to be a proper assumption to make at the stage of R & D planning unless there are solid indications that Federal policy is moving in that direction. Naturally, any conclusion on this score would have to be reviewed year-to-year.

3.5.3 Program Design

The evaluation of problems of commercial adoption should give some key guidance as to the type of R & D program that appears called for in a particular circumstance. Clearly, it is not helpful for government programs to duplicate industry efforts except in very special circumstances. Similarly, little is gained so far as the national interest is concerned if the government expenditures simply replace resources that industry would have committed had the government not undertaken particular programs, although it will be very difficult to tell, in practice, whether or not this is occurring. By the same token, evaluation of the nature of the barriers to commercialization may point to advantageous ways of managing R & D programs. For example, if industry has rejected a particular technical avenue because of a judgement that it will not work, or that it cannot be made to perform at reasonable cost, then little is gained by carrying R & D programs to the point of demonstration of engines in large numbers of vehicles (an activity in the Final Development Stage). Funds are better spent removing the key barriers that form the basis of the industry judgement, and demonstrating that earlier negative judgements were questionable (or finding that industry was right).

If, on the other hand industry has shown considerable interest in a technology (for example in the case of the diesel) but is retarded in its

interest because of key environmental or regulatory issues, then to the extent that the technology appears to have promise the design of the Federal program should focus on the key environmental barriers -- at least until uncertainty about Federal regulation has been removed.

When an engine offers obvious fuel economy and environmental advantages (as in the case of the Stirling, for example), but there is serious doubt about the likely initial cost of the engine, then Federal programs (particularly as they approach the Final Development Stage) are unlikely to be convincing to industry planners if the manufacturing firms themselves are not to some degree involved in the R & D.

In summary, the overall objective of an R & D program carried out by the Federal Government is to advance the state-of-the-art and to develop new technical options which will be adopted by the automobile industry to the overall advantage of the country. Any technical option must pass through the Technology Development and Production process described in Chapter 2, and this means that the design of Federal programs must take into account as much as possible the reasons why the particular technology has not passed through this procedure already. This is an obvious point, it would seem. Unfortunately, it has been too often ignored in R & D planning, or too often the desirable pattern of relationships between industry and government in this area has not been possible for political reasons, or for reasons of resistance on the part of key manufacturers.

Probably the best way of insuring that an R & D program is well coupled into the industry TD&P process is by running the program as a joint cost-sharing with one of the Big Three. This is especially true where manufacturing cost is one of the objectives, which will always be true if the pro-

gram is in the Final Development Stage. In a cost-sharing program the industry has committed its own resources to success, so the incentive structure is there to develop a system which is commercially viable. Government laboratories or companies deriving a profit directly from government R & D (and not producing a commercial product) have an incentive structure which will be difficult to align with the Big Three's TD&P process.

While we have tended to couch much of the preceding discussion in terms of a one-time investment, it is clear that an alternative powerplant R & D program must be, to a great extent, a dynamic one. As the investment is made, the technology will evolve; it will therefore become clearer whether or not technical goals can be met. At the same time, those technical goals will, hopefully, become clearer, although they might not. International and domestic petroleum product prices, the emission standards imposed on the ICE, the technological evolution of the ICE, and all the other factors which lie behind these goals will continue to evolve. If at some point it becomes clear that a given government-supported technology is very unlikely to attain its (uncertain) goals -- the government must be prepared to stop the program.

3.5.4 Conclusion

There are sound reasons why the R & D programs of the American automobile industry may not be carried out at a scale that is justified by the great social interest in this technology. On the other hand, the industry does have a large R & D apparatus and is under constant pressure both from governmental regulation and external competition to stay on top of possible technical options. This means that the Federal program in this area should

seek those opportunities that are not being carried out at adequate scale by industry but which show significant prospects of yielding technical advances which ultimately will be taken up and brought to final stages of development by the industry. In addition, the design of the programs to carry out such Federal research should be worked out in the light of the reasons why industry has not put more funds into particular technologies, and in consideration of the peculiarities of this industry as it goes about its inherently slow process of technological product change.

The various points made above regarding the analysis of potential investments can be summarized in a set of questions that should be addressed to each major expenditure program each time the activity comes up for review. They are the following:

- 1) What are the technical barriers that have prevented the technology from being adopted?
- 2) What are reasonable targets for technical developments designed to improve the overall attributes of a vehicle using this technology?
- 3) What existing R & D programs are there, and why are they structured as they are?
- 4) If existing programs are supplemented by Federal expenditure, what is the likelihood that the various technical barriers can be overcome and targets met?
- 5) At what prices would one evaluate the outcome, should technical achievements be made?
- 6) Does the particular technology offer an opportunity for Federal expenditure that appears to offer large expected present value net social benefits?
- 7) What are the potential barriers to implementation of the technology if it should prove to have the type of benefits that recommend expenditure on it?
- 8) How should the R & D program be designed to overcome the implementation barriers as well as the technical ones?

In most cases, evaluations of this type of individual program are likely to be fairly idiosyncratic, and it may not be possible to find comparisons between programs on alternative technologies or programs on the same technology but at alternative scales. Nonetheless, such a series of questions and analyses should help sort out the bad from the potentially good, and to help allocate available funds where they will do the most good.

A final point needs to be made about the desirable portfolio of government investments in technology of this kind. It is evident that the uncertainties in the calculations suggested above are so great that no one technical avenue is likely to emerge from an overall program analysis as the dominant prospect. The estimates of technical possibilities, prices, Federal regulations, and industry responses, are simply too fuzzy to allow calculations to yield such a satisfying answer. Under these circumstances it is only prudent for those concerned (be they the society as a whole, the R & D planners in government, or industry officials) to carry forward a selection or "portfolio" of alternatives until such point as it becomes more evident where the preferred technical direction for the future lies. This means that one should expect the evaluation suggested above to sort out prospects that are unlikely to prove productive, and to identify a few areas of technical work that are obviously of great promise whatever the circumstance. But between these two extremes there will be a range of prospects which look rather favorable but are subject to great uncertainty as to their ultimate payoff. One should expect the Federal R & D program to carry forward a reasonable number of these in order to hedge against the failure of any one of them to achieve its desired performance.

Thus, in light of all the uncertainties we have expounded upon over the

preceding pages, government investment in alternative powerplant R & D must be viewed as a gamble -- it can be expected to pay off, but we won't find out unless we try it.

4. THE ICE BASELINE

4.1 Background

We have already made the point that the alternative engines are competing to take the place of a firmly entrenched technology -- the internal combustion engine or "ICE". This engine, the reciprocating carbureted gasoline-fueled spark-ignition engine, has been the dominant automobile engine since the early 1900's. Hundreds of millions of these engines have been produced and operated. Extensive production facilities now exist, many of which are relatively new. Mass production methods and the required machine tools have been developed to a high level of sophistication. An enormous amount of experience relating to the design and manufacture of the ICE has been accumulated within the automobile industry. An extensive service industry -- with facilities, trained mechanics, tools and equipment -- has been built up. It is paralleled by an extensive spare parts industry and distribution system. Millions of automobile owners have gained confidence in the ICE, and have developed high and continually increasing expectations of engine performance and reliability. The industry has built up an impressive record of steady improvements in engine design and performance. Most importantly, in our context, the automotive industry has evolved an operating structure with massive engineering resources focused on the continued development and improvement of almost all aspects of its ICE technology.

As discussed above, many factors now combine to make the future of the ICE less secure than it has appeared at any time since it came to dominate

the automotive market beginning seventy years ago. The major uncertainties concerning the future of ICE technology are:

- * Whether the ICE can achieve sufficient control of hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen (NO_x), to meet emissions requirement in the longer-term;
- * Whether the catalyst technology which has been developed for HC and CO control, and may be developed for NO_x control, will be sufficiently durable and maintainable in actual use;
- * How significant special problems associated with this catalyst technology -- e.g., sulfate emissions -- prove to be;
- * Whether the engine fuel economy gains which have been achieved in model years 1975 and 1976 will continue, especially if emissions are further reduced.
- * Whether adequate vehicle driveability (which has deteriorated as vehicle emissions have been reduced) can be maintained if emissions are further reduced.

One fundamental and difficult problem in evaluating alternative engines is, therefore, the expected continuing development of the established ICE technology. The alternative engines are unlikely to be in mass production before the early- to mid-1980's, and it is the production ICE in this future timeframe, and not today's ICE, against which the alternative must be evaluated. Already intensive efforts are being made to adapt today's ICE to the perceived needs of the 1980's. This effort will be

further stimulated by any large or successful R & D efforts on the alternative engines. Also since the alternatives are likely to have higher initial costs, the option of a more sophisticated (and thus more expensive) ICE will be worth exploring if operating gains comparable to the potential of the more promising alternatives can be realized.

Because the ICE has dominated the automobile engine market for so long, there are tremendous development resources available for its further improvement. Substantial efforts are now being made to both improve engine efficiency, emission control technology and vehicle driveability, and reduce initial cost. Potential improvements in the following areas are being sought:

- * Better mixture preparation, and ignition system performance to permit leaner engine operation to improve engine efficiency;
- * More durable and effective catalytic converters -- oxidizing for HC and CO, and three-way with air-fuel ratio feedback control for HC, CO and NO_x -- to minimize the impact of stricter emission standards on fuel economy.
- * Computer control of engine operating variables -- spark advance, EGR, air-fuel ratio -- as a function of engine speed, load and temperature to optimize efficiency at any given emission level and fuel octane rating.
- * Cylinder head and combustion chamber redesign for optimum fuel economy and engine emission control.

On the time scale comparable to that required for developing and introducing alternative engines -- 5 to 15 years -- reasonable progress in most of these areas can be expected. However, the extent of this progress depends strongly on the emission standards in effect over the next ten years or so, on the manner in which these emission standards are eventually promulgated, and on whether the 0.4 g/mile NO_x standard remains as the ultimate but perhaps postponable goal, or is removed as a long-term requirement. The difficulties with the applicable emission standards are compounded by uncertainties in fuel characteristics. Some of the promising ICE development options could use leaded gasoline. This would allow an increase in engine compression ratio due to the higher fuel octane rating (the amount of the increase depending on the amount of lead added, which may be constrained by concerns over lead as a health hazard), and thus an increase in fuel economy. Or catalyst systems which require unleaded fuel may continue to dominate; if so, pressures to increase the octane rating of unleaded fuel are likely to develop. The degree to which increases in octane rating of either leaded or unleaded fuel can be translated into fuel economy improvements depends on the emission standards which have to be met.

A somewhat different issue is the vehicle acceleration capability deemed acceptable to the car-buying public. There has been an erosion of vehicle performance of about 1/4 percent already over the past seven years as a result of meeting emission control requirements. [51] It may be that the public will respond to higher fuel costs by trading off vehicle performance for fuel economy improvement through the purchase of lower power engine options. There is evidence of a modest shift in this direction

already. [52] If this trend continues, then the sensitivity of the ICE baseline to reductions in the ratio of engine power to vehicle weight become important.

We will assume that vehicle performance requirements remain roughly unchanged, and that only unleaded gasoline is available at an octane rating close to today's value. We will estimate approximately the improvement in fuel economy realizable in the 1975-1985 time frame from improvements in the engine alone, at three different emission levels which cover the spectrum of options now being considered:

- (A) No change from 1975 standards (49 states)
(1.5 g/mile HC, 15 g/mile CO, 3.1 g/mile NO_x)
- (B) Proposed 1982 EPA standards
(0.41 g/mile HC, 3.4 g/mile CO, 2 g/mile NO_x)
- (C) Statutory 1978 standards
(0.41 g/mile HC, 3.4 g/mile CO, 0.4 g/mile NO_x)

Note that these estimates are judgemental, since the potential for improvements is not well defined. Nonetheless, they indicate the magnitude of the improvements which can be realistically expected from the ICE under different sets of assumptions. And such estimates must be developed before any meaningful evaluation of the alternative power systems can be made.

4.2 Potential ICE Fuel Economy Gains

Vehicle fuel economy gains, for a given size car, are likely to be realized through many different design improvements. These include changes in the vehicle's shape (i.e. aerodynamics), reduction in weight, improve-

ments in tire construction, as well as changes in engine and transmission. Clearly, vehicle body and tire design changes which improve fuel economy will be applicable to vehicles with alternative engines as well as the ICE. Also, transmission improvements will be realized by the alternatives, to roughly the same degree they benefit the ICE (at least to within the order of our crude calculations).¹ We will therefore include in our baseline engine definition only the basic engine assembly, the induction and ignition systems, cooling system, auxiliaries and complete emission control system. The transmission is not included. (It is worth noting that improvements in the conventional automatic transmission should bring a 4 to 9 percent increase in vehicle fuel economy [53]; and a continuously variable transmission with today's ICE might show a 17 to 30 percent improvement. [53]) Note also that stratified charge spark ignition engines are not included as baseline engine development options; we consider those stratified charge engines with potential for significant fuel economy improvement as sufficiently different from the ICE to be classed as alternative engines. Thus our improved ICE baseline does not include some of the options evaluated as potential ICE improvements in the Rand study. [7]

The most promising ICE-emission control system combinations in terms of potential for fuel economy improvements at different emission standard levels are shown in Table 4.1. These three systems have been examined for their fuel economy improvement potential [54] in the 1975 to 1985 timeframe. The changes in engine design and operation likely to result in improved

¹While this would not be true for electric vehicles, the precise performance of the baseline engine is less important in that comparison.

Table 4.1

POTENTIAL OF DIFFERENT ICE CONCEPTS FOR
MEETING EMISSION STANDARDS¹

HC/CO/NO_x Standards g/mile

<u>Concept</u>	<u>1.5/15/3.1</u>	<u>0.41/3.4/2.0</u>	<u>0.41/3.4/0.4</u>	<u>Comments</u>
Lean Burn ICE: engine modifications, onboard computer, thermal reactor.	Yes	Maybe	No	No sulfate emission problem. Could use leaded fuel and gain in fuel economy.
Lean Burn ICE: engine modifications, onboard computer, oxidation catalyst.	Yes	Yes	No	May be sulfate emission problem. Requires unleaded fuel. May or may not benefit from high octane fuel.
Stoichiometric ICE: engine modifications, exhaust-gas sensor, feedback system, onboard computer, three-way catalyst exhaust gas recirculation.	Full system not required	Full system not required	Probably	Unlikely to be sulfate emission problem. Requires unleaded fuel. Unlikely to be able to benefit from higher octane fuel.

¹In actual use at 50,000 miles; by 1985.

engine fuel economy, and the approximate magnitude of the improvements relative to 1975 values which can be expected by 1985, are listed in Table 4.2. These estimated improvements assume no change in emission standards from today's (1975) levels. Thus, by 1985, reasonable expectations for improvements in vehicle fuel economy (mpg) due to improvements in engine design and operation, for vehicle performance similar to today's, are in the range of 14 to 27 percent, assuming emission standards remain at the 1975 49-state values of 1.5 g/mile HC, 15 g/mile CO, 3.1 g/mile NO_x.¹

At lower emission standards the engine fuel economy will be poorer, and the potential for improvements with time will be less because not all the changes assumed in generating Table 4.2 will be available to the degree listed. An average of several estimates of the impact of stricter HC/CO standards, and then stricter NO_x standards, indicates that in the near-term (pre-1980), imposing standards of 0.41 g/mile HC, 3.4 g/mile CO, and 2 g/mile, NO_x results in about a 10 percent fuel economy penalty relative to 1975 model year vehicles; imposing standards of 0.41 g/mile HC, 3.4 g/mile CO and 0.4 g/mile NO_x would result in an 18 percent penalty relative to 1975 model year vehicles. [55] Presumably, with time, if these stricter standards are imposed, these penalties would be somewhat reduced through continuing engine optimization and improvements in emission control technology. However, just as it is overly pessimistic to assume no gains in ICE fuel economy at these lower emission levels, it is overly optimistic to expect all the engine design and operating improvements that make up the

¹The 3-way catalyst system is not of course required at these emission levels.

Table 4.2

POTENTIAL FUEL ECONOMY GAINS BY 1985¹

<u>Total Gain:</u>	Percent Improvement in mpg ^{2,3}
Conservative estimate	14 - 17
Optimistic estimate	22 - 27

<u>Breakdown:</u>	Percent of Total Gain
Increased compression ratio,	27
Leaner mixture or EGR and reduced pumping work,	42
Combustion chamber and cylinder head redesign,	27
Onboard computer,	33
Increased spark-retard,	- 29
Total	<u>100</u>

¹At 1.5 g/mile HC, 15 g/mile CO and 3.1 g/mile NO_x

²Relative to 1975 model year engines

³Range in values for different ICE concepts in Table 4.1

increase listed in Table 4.2 to be capable of full implementation. For example, it has been estimated that 1976 model year vehicles, due to engine and transmission improvements alone, have on average shown a 9 percent increase in fuel economy. [52] (1976 models in the 49-states met the same emission standards as 1975 models.) Only a part of this gain relative to 1975 would be realizable at lower emission levels. We can, however, say that the relative fuel economy of vehicles, at the three emission levels we have examined, are approximately defined in terms of technology available in 1975, and that the curves of fuel economy improvements due to engine developments over time will diverge. Thus, in future years the differences in fuel economy between vehicles at the three emission levels examined are likely to increase with time.

The appropriate baseline against which to evaluate the alternative engines should include only those improvements which one can confidently expect to be realized. All other options, be they a better ICE or the alternative engines, would thus be compared against an almost guaranteed minimum. We take the conservative estimate in Table 4.2, a 15 percent gain by 1985, to be this lower bound, if there were no change in emissions requirements. Figure 4.1 shows this minimum expected gain as a solid line over the period 1975 to 1985; the shaded area above, labeled A, represents the range of potential improvements above this minimum which might be realized but cannot be guaranteed.

The solid lines in Figure 4.1 at the bottom of areas B and C indicate our estimates of minimum fuel economy at lower emission standards: 0.41 g/mile HC, 3.4 g/mile CO, 2 g/mile NO_x; and 0.41 g/mile HC, 3.4 g/mile CO and 0.4 g/mile NO_x, respectively. We have taken the fuel economy

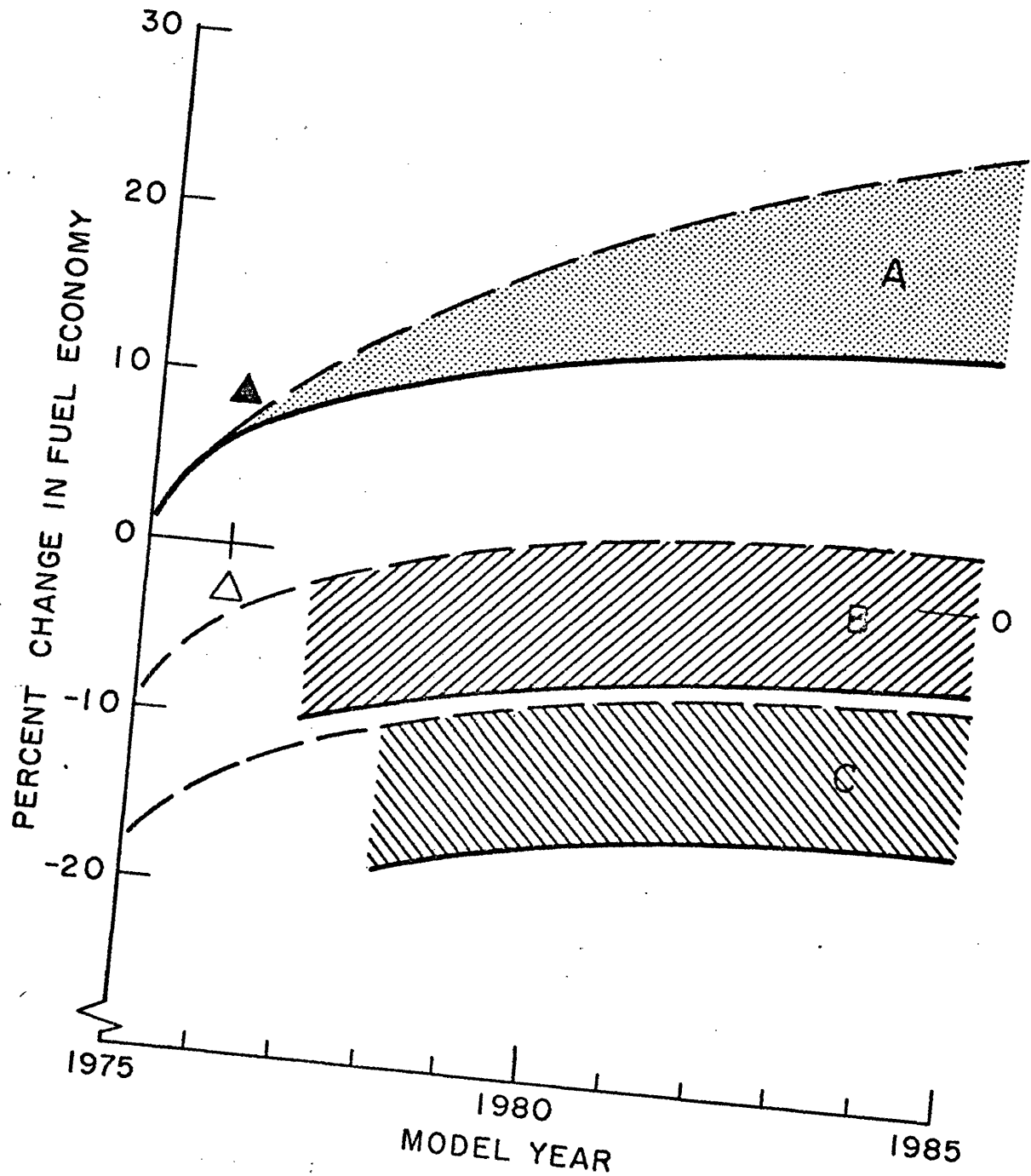


Figure 4.1
CHANGE IN ICE FUEL ECONOMY AS A FUNCTION
OF EMISSION STANDARD AND YEAR.
(Emission Standards (HC/CO/NO_x):
A, 1.5/15/3.1; B, 0.41/3.4/2; C, 0.41/3.4/0.4)

penalties of 10 and 18 percent, relative to 1975 values, and then assumed that the penalty relative to the no-change-in-standards case remains constant with time. The shaded areas above each line again indicate our estimates of the possible but in-no-sense guaranteed improvements above these minimums. The two data points for 1976 show average 49-state vehicle fuel economy change relative to 1975 model year (the California standards of 0.9 g/mile HC, 9 g/mile CO and 2 g/mile NO_x are halfway between our levels A and B). [52] The estimates are in reasonable agreement with the data.

4.3 Initial Engine Cost

Since we will be making comparisons between the baseline and the alternative engines on a total life-cycle cost basis, the impact on the initial cost of the ICE, of the engine changes we have described, must be assessed also. The baseline engine cost can be expected to increase due to changes made to improve fuel economy, and will further increase if emission standards are reduced below today's value.

Careful evaluations of the effect of the changes listed in Table 4.2 on initial engine cost are not available in the public domain. Our rough estimate of their impact would be in the \$50 to \$100 range, at today's emission standards. More accurate estimates of the effect of stricter emission standards are available [8, 56]; these do include some of the potential improvements listed in Table 4.2, however. Values of the initial engine cost increases estimates for an intermediate sized engine in these studies are given in Table 4.3; they correspond to different

Table 4.3

IMPACT OF STRICTER EMISSION STANDARDS ON ICE INITIAL COST

Change in Standards (HC/CO/NO _x in g/mile)	Initial Cost Increase	
	NAS ¹	JPL ²
1.5/15/3.1 to 0.41/3.4/2	\$65	
1.5/15/3.1 to 0.41/3.4/0.4	\$190	
0.41/3.4/2 to 0.41/3.4/0.4	\$125	\$65

¹Near-term, pre-1980 [56].

²Mature technology, mid-1980's [8].

timeframes with near-term being pre-1980, and "mature" being mid-1980's. The total initial engine cost penalty of both changes to improve fuel economy and changes required to meet stricter emission standards could be up to about \$250, but by the mid-1980's is likely to be substantially less than this figure.

An accurate estimate of this penalty is not required for our purposes because the increase in initial engine cost due to stricter emission standards is greater than the increase due to fuel economy improvements, and the fuel economy losses resulting from stricter emission standards have a much greater impact on total life-cycle cost than do either of these initial cost increases. For example, a 20 percent fuel economy decrease, at 55¢/gallon fuel price and 20 mpg baseline fuel economy, at 7 percent discount rate increases total life-cycle costs by about \$500. The increase in initial engine cost is likely to be less than one-third this value.

However, we do need an approximate estimate of the initial cost of the baseline engine in the mid-1980's. The JPL estimate of the mature ICE initial cost will be used for this purpose. [8] Their figure of \$1320 for a 150 hp engine with a 3-way catalyst emission control system at standards of 0.41/3.4/0.4 g/mile HC/CO/NO_x can be adjusted for a higher NO_x standard, and the exclusion of transmission and battery from the definition of the engine to give an initial engine cost of about \$900. We will use this figure as the estimated cost of the mid-1980's baseline ICE in our subsequent evaluations.

4.4 Conclusions Regarding the Baseline

The important conclusions regarding the mid-1980's ICE, as a baseline against which to evaluate the alternative engines, are the following:

- 1) With no change in emission standards, the minimum expected fuel economy improvement by 1985, due to engine design changes alone, is about 15 percent relative to the 1975 fuel economy levels. The maximum potential gains are higher of order 27 percent, but we cannot be certain these larger gains will be realized.
- 2) Changes in emission standards have a tremendous impact on these estimated improvements: a reduction from today's standards to 0.41/3.4/2 g/mile HC/CO/NO_x, would result in vehicles with about 15 percent worse fuel economy by 1985; a reduction to 0.41/3.4/0.4 g/mile HC/CO/NO_x would result in vehicles with about 25 percent worse fuel economy by 1985 (worse than the contemporary ICE at today's standards).
- 3) Both changes in engine design to improve fuel economy and changes to meet stricter emission standards will increase initial engine cost. By the mid-1980's, these initial cost increases, while significant (of order \$150), are expected to be considerably smaller than the changes in life-cycle costs that result from fuel economy gains or losses.
- 4) The uncertainty in estimates of the fuel economy of the 1985 ICE is therefore very large; it could vary from 15 percent worse to

about 27 percent better fuel economy than the 1975 ICE. The largest part of this uncertainty results from uncertainty as to the applicable emission standards; the uncertainty in the extent of fuel economy improvements alone is of order ± 5 to 10 percent.

- 5) We conclude that alternative engines are more attractive relative to the ICE at emission levels substantially below today's values than they are at today's standards. Also, at emission levels close to today's levels, advanced ICE technology offers fuel economy gains comparable to those offered by the alternative engines.

5. THE STIRLING ENGINE

5.1 Introduction

In Chapter 3 of this report we developed the thesis that the incentives provided the automotive industry to develop and introduce major technological changes in automotive power systems were inadequate relative to social needs and that a government role in supporting R & D in this area might well be justified. In this chapter we examine in detail a particular technology, the Stirling engine, to determine the possible impact the government might have in advancing this technology and how such impact might best be achieved. Because it is impossible to quantify the complicated set of incentives and disincentives faced by the industry, our judgement that they are generally inadequate will provide an important backdrop to the judgements that will be made in the remainder of this chapter.

The analysis will follow generally the formulation of the problem as developed in Chapter 3. Here, however, we will be able to deal with specifics in many areas which Chapter 3 left ambiguous. On the other hand, one thing we will also be able to demonstrate clearly is the magnitude of the uncertainties involved in many important areas.

The Stirling engine is representative of the category of alternative powerplants which are "advanced" heat engines that are very different from the ICE, which have the potential for high vehicle fuel economy and low air pollutant emissions, but which require a substantial development effort before these attributes can be demonstrated in engines at competitive cost. For the Stirling engine, the principal issues in need of analysis are: 1) the present status of the technology and the R & D programs now underway,

2) the potential social benefits which might be obtained from replacement of the ICE by the Stirling and whether these are worth the likely government costs, and 3) the barriers which have prevented, or might prevent in the future, a socially beneficial Stirling engine from becoming a commercial reality and how government-supported R & D might overcome these barriers. These three issues are addressed in detail in the following three sections of this chapter. The chapter closes with a summary and a set of conclusions. A review of the status of Stirling engine technology is found in Appendix A to the report.

This chapter considers the Stirling engine in isolation among the alternative powerplants, i.e. it compares it only to the ICE (as that engine will evolve). We will conclude, however, that the Stirling engine is unique enough and attractive enough that a government-supported development program should be undertaken, independent of action taken concerning the other alternatives. No other alternative offers the following combination of characteristics: 1) air pollutant emissions almost certain to meet the statutory (original 1976) emission standards, 2) fuel economy substantially superior to the present ICE, 3) ability to burn a broad-cut distillate fuel, 4) no major integrability problems, and 5) a major American motor vehicle manufacturer requesting government funds for a cost-sharing agreement and development program. While investments in one or more of the other alternatives may also be likely to be socially beneficial, and the government should probably support more than one, the Stirling system should be one of those supported. This summary evaluation can be arrived at only after the careful documentation and analysis which is the remainder of this chapter.

5.2 Status of the Technology and Current R & D Programs

In this section we will first summarize very quickly the history and present status of the Stirling engine, then discuss the likely attributes of a Stirling-powered passenger car which could be developed and marketed before the 1990's and, finally, discuss the merits of the Stirling engine as a competitor to the diesel in the heavy duty prime mover application. We have relegated to Appendix A a detailed discussion of the history and present status of the engine and its crucial components, together with the technological details of the history and current status of the R & D programs which have brought the technology to its present state. Our analysis depends on a number of judgements which can only be made based on the detailed type of knowledge presented in the appendix; it will therefore be necessary reading for those who wish a fuller justification of the conclusions reached in this and the next section and the chapter as a whole concerning the response of the technology to an input of government support.

5.2.1 A Brief Description of the Modern Automotive Stirling Engine

The Stirling engine is characterized by the use of a continuous-flow combustor from which heat is transferred to a gaseous working fluid in a sealed mechanical system; the gaseous working fluid is compressed, heated, expanded against a piston connected to an output shaft and cooled, in a closed cyclic process.¹ The combustion system is external to the working fluid, in contrast to the ICE, diesel or gas turbine, where the fuel and air are combusted under pressure and expanded directly to produce work. The use of a gaseous working fluid contrasts with the condensible material

¹See [57-59] for detailed technical discussions of the Stirling cycle engine.

(usually water) used in a Rankine cycle system (also an external combustion system) where condensation and evaporation play significant roles in the thermodynamics of the cycle.

The two crucial features of the system which make it interesting as a potential automotive powerplant are: 1) the fact that the theoretical thermodynamic efficiency is limited only to the maximum obtainable by any heat engine operating between the same maximum and minimum working fluid temperatures (the "Carnot" efficiency); so that with modern heat-resistant materials relatively high efficiencies can be obtained using a relatively simple thermodynamic cycle (the "Stirling cycle"), and 2) the continuous-flow external burner which allows the combustion process to be controlled much more precisely than in intermittent combustion systems, so that air pollution emissions can be limited without degrading engine performance. The continuous combustion also eliminates one of the major sources of noise and vibration found in the ICE and diesel, namely the rapid pressure rise associated with the intermittent internal explosions, and makes the combustion system efficiency relatively insensitive to the particular qualities of the fuel (again in notable contrast to the ICE and diesel).

The modern Stirling engine is a complex device requiring many highly sophisticated components for efficient, reliable operation. The Ford Motor Company is now engaged in a program to develop a system suitable for the passenger car application; a cutaway drawing of the engine now in vehicle testing at Ford is shown in Figure 5.1. The "guts" of the engine are within the sealed system for the cyclic processing of the pressurized gaseous working fluid. Most modern systems use a set of cylinders with one or two pistons in each for compressing and expanding the gas (hydrogen) and moving it

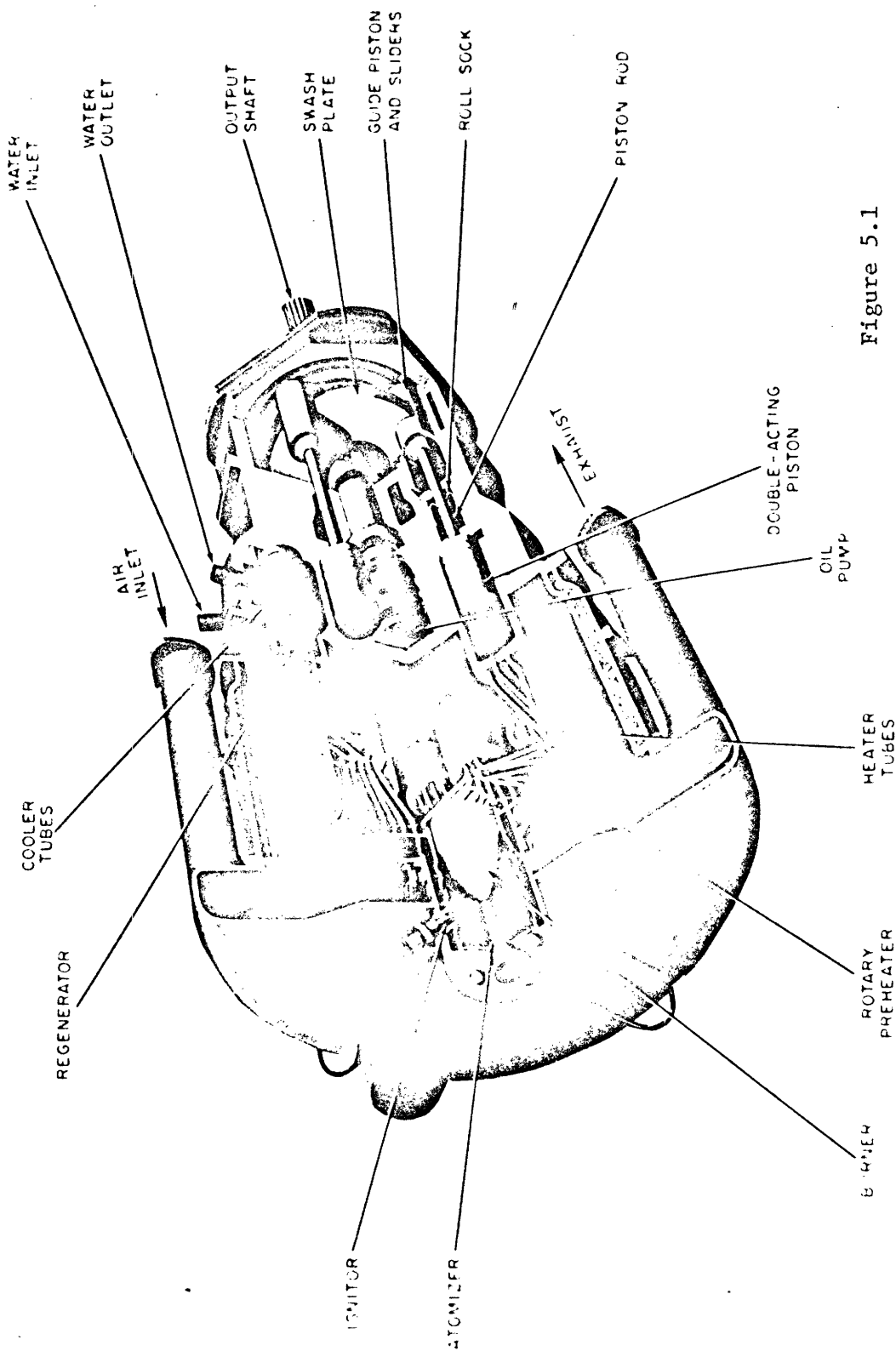


Figure 5.1
 CUTAWAY DRAWING OF FORD-
 PHILLIPS PROTOTYPE ENGINE
 (Courtesy of Ford Motor Co.)

through the heater and cooler. For each cylinder there is at least one regenerator in which part of the working fluid's heat content must be stored during each cycle. The passages within the working gas flow system must be carefully designed to minimize the parasitic losses incurred in merely moving the working gas around, and the regenerator must be carefully designed for rapid absorption and release of heat with minimal contribution to the flow losses. There are a number of different ways in which the pistons, regenerators, heaters, coolers and intervening passageways can be configured; the systems now under consideration for automotive use are "double-acting" in that a single piston in each cylinder serves both to take work out of the system and to move the working fluid around.

Because the working gas is highly pressurized, critical features of the system are the external hydrogen seals, i.e., the sealing mechanisms at the points where power is transferred out by the motion of the piston rod. Two types of seals are presently under consideration -- the roll-sock seal invented by Philips, and the simpler but less effective sliding seal. Although most components of the system can be made with relatively conventional materials and technology, an unusually demanding situation occurs in the heater head, which must contain the high pressure hydrogen while continuously held at or above the maximum working gas cycle temperature. It is therefore a significant cost reduction challenge, because in order for the engine to attain its high efficiencies, peak cycle temperatures are used which press the limits of materials technology, and thus expensive superalloys are required. A development of major significance would be the use of ceramics to replace the superalloys in the heater head. This would allow some increase in peak cycle temperature and thus efficiency; more importantly

it could effect a major cost reduction. However, while R & D programs are currently underway on high temperature load-bearing ceramic components, the development of techniques for manufacturing such components in quantity would have to be considered a major technological advance.

The burner, in which fuel and air are mixed and combusted must be carefully designed to limit the quantity of air pollutants formed. Preceding the burner in the air-flow path is the air blower, which, due to the extremely low noise and vibration level of the engine proper, becomes an important noise source. The hot combustor product gases are directed along the outside of the heater head, through which the bulk of their thermal energy is transferred to the working fluid. An air preheater is used to increase the overall system efficiency by transferring as much as possible of the thermal energy remaining in the burner exhaust gases after they have passed through the heater head to the stream of fresh air entering the burner. Rotating ceramic preheaters as well as stationary metal devices have been demonstrated.

Three crucial and complex control systems are required to provide the necessary engine response to the vehicle operator's demands. Power control is accomplished either through some alteration to the geometry of the working gas flow system or by actually changing the mass of working fluid in the system. It must be sufficiently responsive for the engine to meet the requirements of its duty cycle, and not excessive in cost. The fuel and air control systems respond with the power control system so that the requisite amount of heat is generated for a given power output, and they must be coordinated together to meet the requirements of the burner.

Finally, a drive system is required to convert the reciprocating motion

resulting from the pistons to the rotary motion required of the transmission and drive shaft. Minimum weight and bulk are its key attributes. Either a swashplate or conventional (ICE-type) crankshaft can be used (with cross-head pistons), depending on the configuration of the cylinders.

5.2.2 Review of the History and Present Status of R & D Programs¹

As patented in 1816 by the Scottish minister Robert Stirling, the engine used a coal- or wood-fueled fire to heat compressed air in a cylinder; the air was then expanded against a piston and the resulting power used for, among other things, pumping water from coal mines. Thousands of such "hot air" engines were built during the nineteenth century, especially in applications where a higher degree of safety was required than was available from the steam engine. However, the use of air at low pressure limited power output and the steam engine went on to become the prime mover behind the industrial revolution.

The modern development of Stirling cycle power systems has principally been accomplished at the Philips Research Laboratories, Eindhoven, Netherlands, the main component of the research arm of N.V. Philips.² Their program began in 1938; it was initially intended to meet a demand for quiet generation of electric power for radios at remote sites, but the invention of the transistor virtually eliminated the demand. The automotive application

¹Much of the historical material presented here is taken from personal interviews.

²Philips has published a number of historical reviews of the technological and programmatic history of their efforts [e.g. 60-62].

is only one of a large number that Philips has explored in its continuing efforts; estimates of Philips' total investment in Stirling technology range up to \$100 million. Discussion of some of the many important advances made at Philips is contained in Appendix A.

As a corporation whose principal interest has been and remains in the electronics area, Philips has constantly sought licensees in the engine manufacturing business who would apply Philips' technology to the development and production of practical systems. During the period 1958 to 1970 General Motors was a licensee of Philips. The Allison and Electro-Motive Divisions and the Research Laboratories all built experimental motors for a variety of potential applications, including underwater systems for the U. S. Navy (the low noise and vibration characteristics of the engine would make it advantageous for torpedoes), engines or generators for the U. S. Army (again inaudibility was important), and auxiliary powerplants for space satellites for the U. S. Air Force (where it would be run indirectly from solar heat). In all, a great deal of experience and expertise was accumulated -- involving over 25,000 hours of operating experience [63] and an investment of \$10-15 million. For various reasons, none of these efforts resulted in a significant government procurement. Although in the late 1960's GM looked closely at the emissions potential of the engine and built two highly experimental vehicles using small Stirling engines (one a hybrid with an electric motor and batteries, the other running off a heat store), GM concluded that the engine did not have the potential to become a passenger car powerplant (in contrast, for example, to its handling of the gas turbine). Nitrogen oxide emissions, weight and bulk, cooling (i.e. radiator size), sealing, cost and response time have been cited as the key problem areas. [64] Since 1970 GM's

Stirling engine activity has been confined to maintaining cognizance of external developments.

Philips' second important licensee was KB United Stirling (Sweden) AB & Co., a firm founded in 1968 for the sole purpose of developing and marketing Stirling cycle engine technology. Its (equal) co-owners are Kockums Mekaniska Verkstads AB, the sixth largest shipbuilder in the world, and Forenade Fabriksverken (FFV), a defense manufacturer owned by the Swedish Government. The company now employs about 90 people. The motivation for the formation of United Stirling was a mutual interest in Kockums and FFV in quiet and efficient engines for marine use, especially in submarines. United Stirling's first order of business was to work out a technology licensing arrangement with Philips. The initial plan was to develop as rapidly as possible an engine based on the technology then most prominent at Philips, and to market it for uses where the advantages of high efficiency, clean exhaust, and low noise and vibration would outweigh the relatively high initial cost. It had been hoped that the submarine, the city bus, or underground mining equipment might provide such applications. The engine which resulted in 1971 turned out to be too heavy and expensive for these markets, although it did have low noise, vibrations and emissions, and a thermal efficiency between that of an ICE and a diesel. With this experience, the company then decided to orient its development work more specifically toward the prime mover field, where the increasingly stringent emissions and noise controls would tend (they hoped) to increase the attractiveness of the Stirling relative to the diesel. A cylinder configuration of the conventional "V" type was adopted along with crosshead pistons and a conventional crankshaft.

In 1968 the two large German firms M.A.N. and Motoren-Werke Mannheim AG

(MWM) decided to undertake a joint Stirling engine development program. Both companies manufacture a range of diesel engines. With a total technical employment in their Stirling program of about 30, this effort is less than half the size of the other two. The group cooperates closely with Philips, from whom they have purchased a license; less closely with United Stirling. The M.A.N. - MWM Group was formed from the beginning with a long-range program in mind. Managements' opinion was (and is) that the engine's emissions, noise, fuel economy and fuel tolerance characteristics might in the long run dominate over the engine's high cost, but that there was not much hope of a successful product in the near term. Furthermore, they are interested in developing a technology which would ultimately be applicable in some large part of the broad range of markets for which they now make diesel engines. The M.A.N. - MWM Group therefore has not sought to build a prototype for a specific application.

With the loss of General Motors as a licensee in 1970, Philips began an active search for a replacement with comparable interest and capability in the mass production and sales of passenger car engines. At about the same time, Ford was conducting a major internal review of its alternative power-plant programs, prompted largely by the rapid rise in importance of the air pollution issue.¹ Discussions were held, with special emphasis on the problems identified by GM. A nine-month study was initiated, including emissions testing on a burner and detailed examination of various packaging approaches. Ford concluded that all of the major problems appeared amenable to solution, although a major development program would be required. In July, 1972, Ford and Philips signed an agreement for a seven-year joint engine development

¹Ford has discussed the history of its Stirling engine program in two public documents [57,65].

program, including a licensing arrangement. Ford subsequently signed a licensing arrangement with United Stirling, forming a three-way pool with regular technical interchanges.

The first phase of the Ford-Philips program (corresponding roughly to the latter efforts of the Initial Development Stage discussed in Chapter 2) centers on the design and fabrication of a 170 hp Stirling "research demonstration" engine. It is comparable in its gross attributes to the 351 CID ICE in a Ford Torino, an "intermediate" size car with a curb weight of about 4,200 lbs. Three of the engines have been built; two were to be installed in vehicles for extensive field testing. Philips has had responsibility for the design and fabrication of the engine proper; this program has come to consume the bulk of Philips' Stirling engine effort. Ford, with a much smaller present manpower commitment, has been responsible for those accessories which are standard automotive items, and the provision of packaging and performance requirements to Philips. In October, 1975, the first Stirling-powered Torino arrived in Dearborn and, at this writing, is undergoing testing.

The technical goals of Phase I of the program are, in summary, to develop an engine which would allow the Torino to: 1) meet the statutory (original 1976) emissions standards, 2) provide a substantial improvement in fuel economy, 3) maintain its performance, and 4) have all other non-pecuniary attributes which would be acceptable to consumers, including noise, start-up time, driveability, and maintenance (especially working gas recharge period). System durability and reliability will be the focus of the vehicle testing program. This is the first time a Stirling engine has been designed to meet a specific set of vehicle requirements. A crucial feature of the Phase I

program is that no manufacturing cost considerations have been explicitly incorporated into the engine design.

It now appears that the program will meet all its primary objectives, and that Ford and Philips will proceed into the second half of the joint program, Phase II, corresponding to the early efforts of the Final Development Stage discussed in Chapter 2. However, the engine as it stands is a device which could not be mass produced at a cost within even several times that of present engines. During Phase I Ford has identified the key high cost components of the present system. No significant efforts have yet been made at developing lower cost items, however. Thus Phase II, presently planned to cover roughly the years 1976 through 1979, will involve several complete design iterations with fabrication of improved components and engines, focusing on cost through minimizing the requirements for superalloys and designing components amenable to mass production on modern high volume transfer lines. Simultaneously, studies of the application of the engine to vehicles of other sizes will be conducted. An important feature of Phase II will be the active acquisition by Ford of all the relevant engine design capability and "know-how", i.e. the technology, from Philips. The results of continued developments by Philips, United Stirling, and future licensees would of course be incorporated to the extent possible. Key engine and engine-vehicle tradeoffs would be made during this period.

If Phase II is successful in developing an engine which has the potential for being manufactured at the suitable cost, Ford estimates that a minimum of two more years of development would be required, centered on production engineering, at the end of which the final design, manufacturing techniques, and thus cost figures, would be firm and the Final Development Stage would

be completed. During this stage Ford would expect to be intimately involved with potential suppliers for a number of the critical components. Ford estimates the total cost of the Final Development Stage at \$100-200 million "to be shared [they hope] by Ford, ERDA, subcontractors and licensees". [66]

Again assuming continued success, in early 1982 or so a positive Introduction Decision would be made and a four-year "Production Program" would be undertaken, resulting in the introduction into the marketplace of Stirling-powered vehicles in late 1985. Ford estimates the total cost of the Production Program (or "Introduction Stage"), at \$500 million to \$1 billion, including the first plant. Ford emphasizes that the 1985 date is a purposely optimistic estimate, based on minimum reasonable estimates for the length of the development stages, and requiring levels of funding which are larger than Ford is willing to commit by itself.

Ford is actively seeking government support for its Stirling engine development program. On July 9, 1975, a \$550,000 contract was signed between Ford and the Energy Research and Development Administration (ERDA) for the design of a 80-100 hp Stirling engine powerplant to power a subcompact (curb weight 2500-3000 lbs.). This represents a contribution to the scalability studies of Phase II of the Ford-Philips program. Ford would like to see heavy government support of component and prototype engine developments in the stages up through and including the Final Development Stage.

5.2.3 Attributes of the Automotive Stirling Engine for the 1980's

In this subsection the overall development status and attributes of the engine as a system will be discussed. Two points should be noted at the out-

set. First, it is really the attributes of the vehicle as a whole that are of concern here, not those of the engine alone. Thus engine attributes must be discussed very carefully, and can really be evaluated only as part of a full vehicle design. The most relevant example of this consideration is the tradeoff between engine weight and efficiency. This section, however, will deal principally with engines; discussion in the vehicle context will be postponed to Section 5.3. Second, in this subsection we will minimize the use of quantitative attribute values, because such numbers are very difficult to develop in a meaningful way. Each requires a host of technical qualifications, and as stated above, are of limited usefulness outside of a vehicle context. For example, the thermal efficiency of the Stirling engine depends heavily on: coolant temperature, driving cycle (if any, often point values are used), and very careful accounting of necessary accessory losses, among other things, and, in any case is not meaningful outside of a vehicle context due to the impact of engine weight on vehicle weight. Similarly, specific power is difficult to compare between engines due to problems of accounting for accessory volume and weight. We will therefore primarily rely in this discussion on qualitative comparisons with other systems. A major difficulty in such comparisons (qualitative or quantitative), pervasive throughout this report and explicitly addressed elsewhere, is just what system to compare the Stirling engine to. In this subsection we will generally compare the Stirling to the present ICE, and then use the discussion from Chapter 4 to extend that to the future ICE.

In Appendix A we discuss at some length the status of the key components of the Stirling system. An automotive engine is, however, more than a collection of components -- it is a carefully integrated system whose gross

attributes are the result of a complicated set of tradeoffs which include choices among competing component concepts and the design parameters of the components chosen. As discussed above, many hours of running time have been accumulated on Stirling engines in laboratories in the United States and Europe; most of these hours were focused on the performance and durability testing of key components in laboratory engines not designed to be commercially utilized. It is not a trivial matter, then, to discuss the attributes of an optimized engine system based on known component performance characteristics. This capability has now largely been attained (or nearly so) at Philips through the use of computer simulations. Attribute levels given here, however, are based on the results of engine test data and a consensus of expert opinion.

As discussed above and in Appendix A, various component concepts have accumulated different levels of experience behind them, and thus the amounts of development effort required for incorporation into a practical engine are very different. We will therefore characterize the technology here by dividing it into a "First Generation System" (FGS) and "Advanced Systems". The FGS is defined as utilizing the component concepts of the Ford-Philips, United Stirling and M.A.N. - MWM groups which have reached the development status where questions of their performance have been largely resolved, although issues of cost and (to a lesser extent) durability remain unresolved. Thus the FGS utilizes a double-action configuration with either swashplate or crankshaft drive, mean pressure (with a bypass) or pressure amplitude (dead volume) control, and roll-sock or sliding external seals. Most significantly, the FGS uses no ceramics in the heater head or any other load-bearing component (although it may well utilize a ceramic core in its pre-

heater). Advanced Systems might incorporate ceramic materials, especially in the heater head, a heat pipe, a variable-angle swashplate, or new concepts which have yet to be formulated. Table A.1 of Appendix A summarizes the status of the key components.

The FGS is the only Stirling system with a chance to make it to the marketplace before the late 1980's, because incorporation of any advanced concepts would most likely significantly extend the development program schedule. It is not at all certain that the FGS will make it to the marketplace; this obviously depends on the success (and thus the magnitude) of ongoing and future development programs. The Introduction Decision is based on comparing a set of Stirling vehicle attributes with a set of marketplace and government criteria; both are dynamic (aside from being uncertain). If the FGS does not meet the standards relevant for the mid-80's, maybe an Advanced System will meet the more demanding criteria relevant for its later potential introduction date; viz. structural ceramics may ultimately be necessary for a commercially successful Stirling engine. In any case, since any Advanced System will require a significant technological advance to make it out of the Initial Development Stage, we focus here on the FGS for forecasting the attributes of a Stirling engine which, given an adequate R & D program, could probably be brought to the marketplace before 1990.

The technological status of the FGS can be approximately characterized in the following simplified way. It has demonstrated (simultaneously) acceptable levels of all the requisite powerplant attributes except initial cost. These attribute levels are now reasonably well known (uncertainty in the efficiency will be discussed below), but its initial cost (at a production volume sufficient to utilize available economies of scale in manufac-

turing) is relatively unknown, bounded roughly on the low side by the cost of a similarly-sized ICE and on the high side by several times that. This statement is based on the results of extensive dynamometer testing of FGS components and complete engines by Philips and its licensees, on the results to date of the Ford-Philips program, and the fact that it appears that the vehicle testing of the Ford-Philips engines has indicated that it meets (or exceeds) all the key requirements in the laboratory.

This characterization will prove to be very useful for purposes of our economic analyses because it will allow us to deal with the economics in a very simple way. We will treat initial cost as the key unknown in Stirling technology, and thus the focus of the R & D effort, and we will examine the impact of the other key uncertainties (such as government policies and fuel prices) on the decision criterion for initial cost. This characterization deviates from reality in two important respects. First, even in the simple economic model we will use in Section 5.3, the decision criterion for the engine will be a first-cost/efficiency attribute pair. This is because the efficiency of Stirling engines may be increased somewhat during the R & D process. However, this will be relatively independent of the engine cost (as long as the peak cycle temperature is kept at the materials technology limit, as is expected), so we will treat engine efficiency as an independent uncertainty rather than as the focus of R & D. Second, the existence of significant design tradeoffs between initial cost and air pollutant emissions, maintenance costs, durability, or other key attributes would void this simple characterization. In fact, Stirling engine experts feel that none of these tradeoffs are likely to be significant -- the major focus of future R & D efforts will be the reduction of engine cost, and the other attributes

will probably not suffer significantly in the process. The uncertainty remaining in FGS technology, because it has never been subjected to road testing, is significant, especially as to maintenance and durability, so the question of design tradeoffs against initial cost does, however, remain open.

Only one detailed estimate has been published for the initial cost of the Stirling engine; it was by JPL. [8], They made consistent estimates for the total costs of the ICE, at two emissions levels, and the Stirling system (as well as for the other alternatives). Their total cost estimates include not only the direct manufacturing cost, but also the engine's proportional share of the overhead and profit at the various stages between the engine plant and the showroom; this is correct as an indication of the total resources consumed in the engine as delivered to the customer. Their estimate also includes all the relevant engine auxiliaries. Their "Otto-Engine Equivalent" Stirling requires about 20% less rated horsepower than the ICE; it costs 1.2 to 1.3 times as much, depending on the emissions levels of the ICE. However, the horsepower advantage is very dependent on the specific torque-speed curves of the projected Stirling and the particular ICE chosen, and the "equivalence" criterion they used (a combination of 0-60 mph acceleration time and distance covered in 10 seconds from a standing start). There are substantial uncertainties in the torque curve comparison and whether this equivalence criterion is the correct one. Another important cost comparison, then, is at the same rated power; in this case their ratio of costs is 1.6 to 1.7, depending on the ICE emissions and the Stirling cost scaling procedure. Furthermore, the Stirling cost could be substantially higher, as there is little experience in estimating mass production cost for superalloy components. Our original citation of a Stirling cost from one to

several times the cost of the ICE remains the crucial uncertainty of the system; one which only an R & D program will resolve.

Table 5.1 summarizes the attributes of the FGS. As stated above, initial cost aside, the engine has the potential for attaining an attribute set at least as good as that of the present ICE. We expect some changes in the attributes of the ICE between now and the 1980's, most likely in emissions, fuel economy and initial cost, as discussed in Chapter 4; the impact of these changes on the economics of the future Stirling relative to the 1980's ICE will be discussed below. The three areas where some further uncertainty remains are maintenance requirements, start-up and safety (other than efficiency). Each is an attribute for which consumers in general have high expectations due to their experience with modern ICE-powered vehicles. To the extent that maintenance requirements impose no new non-pecuniary burdens on the owner (such as having to take the vehicle in for servicing more often), then maintenance becomes an operating cost which can be presumably incorporated with initial and fuel costs into the life-cycle cost considerations discussed below. The start-up and safety issues are much more difficult to deal with. These attributes may turn out to be slightly inferior to, or at least somewhat different from, those of ICE-powered vehicles. It is, therefore, not easy to predict consumer reaction to them, and makes the Introduction Decision a more difficult one for the manufacturer. This is especially true of the hydrogen safety issue which may draw an irrational consumer response. The low noise and vibrational energy output of the engine and its possible maintenance advantages are similar features in the positive direction which may balance the safety and start-up problems out. At this time, however, none of these features seems individually of crucial significance,

Table 5.1

ATTRIBUTES OF THE FGS STIRLING ENGINE

<u>Attribute</u>	<u>Importance</u>	<u>Status</u>
Initial Cost	Critical for consumer acceptance.	Somewhere between one and several times that of the ICE at the same power; will be the focus of future development efforts.
Emissions	Legal requirement, although relevant (future) levels unclear.	Meets tightest proposed standards (original 1976) on gasoline, durability probably no problem, emissions when run on other fuels not known.
Efficiency	Key consumer and legal requirement, and of social value	Between present ICE and diesel (either average over Federal Driving Cycle or at peak), 25% over present ICE and possibly more.
Weight	Key factor in cost, vehicle design and vehicle performance	Total system weight approximately equal to that of present ICE.
Packagability (shape and volume)	Key in determining whether major vehicle modifications needed.	No major problems. (Radiator size and system length with swashplate drive require some vehicle modifications.)
Torque-speed curve shape	Determines transmission requirements (and thus influences vehicle cost).	Can utilize present transmissions.
Noise	Consumer and socially appreciated attribute; will become legal requirement.	Substantially superior to ICE; extremely quiet.

Table 5.1 (Cont'd)

Vibration (smoothness)	Consumer requirement; impacts on vehicle design.	Excellent, superior to ICE.
Power response and driveability	Key consumer requirement.	Satisfactory (will meet consumer expectations).
Maintenance requirements (and response to abuse and neglect)	Key consumer requirement.	Probably satisfactory, although uncertain. Hydrogen make-up requirement a potential problem, oil changes relatively rare.
Starting characteristics	May be consumer requirement.	Start-up certain but some delay required before vehicle operation (less than 20 sec.).
Safety	Consumer and possibly legal requirement.	Probably no real problem; studies underway.
Design versatility (scalability)	Key in long-run production cost.	No apparent problems; studies underway.
Fuel versatility	Will allow use of less expensive fuels.	Emissions output and relevant emissions regulations are uncertain, early availability of low-cost fuels unlikely.
Durability	Consumer requirement.	Equal or possibly superior to ICE.

and they are highly uncertain on the "positive" side in that they will most likely improve as development efforts continue. The system's durability is worth a final comment. This will remain uncertain until substantial road-testing in vehicles is completed. There are presently many complex systems which are important to the engine, but these would presumably be maintained or replaced, as long as the expensive principal components of the engine proper are in functioning order (excluding consideration of other vehicle components, such as the body). Because the engine proper must be well sealed, and because the vibrational output of the engine is so low, it is expected that the system's durability will, if significantly different from that of the present ICE, be superior.

While there are other technical uncertainties which are important, then, the dominating uncertainty in the attributes of the FGS Stirling is its initial cost. Because the focus of development efforts to date has been on achieving other attributes at whatever cost necessary, present systems use quantities of expensive materials, manufacturing techniques and complex components which would never be considered for a production engine. Major efforts aimed at system cost reduction have not been undertaken. Furthermore, it is extremely difficult to forecast the degree of success which will be attained by such forthcoming cost reduction programs. As the Phase I portion of the Ford-Philips program draws to completion, Ford has identified six components as potentially high cost items: the heater, preheater, inter-cooler, fuel control, power control, and two-speed accessory drive. 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 from one to several times that of a comparable ICE.

That the fuel economy of a FGS Stirling-powered vehicle will be substantially superior to that of present ICE-powered vehicles is not in doubt. Ford fuel consumption data taken on dynamometer tests has shown a 47% improvement over the baseline 1975 Torino ICE-powered vehicles controlled to California 1975 emissions standards, on a driving cycle consisting of no transients, only a series of constant speeds. Based on these results, Ford has stated that the engine "should easily be able to meet our 25% improvement objective" [63] referring to fuel economy measured on Ford's "city-suburban" cycle, which includes substantial transient operation (the Ford-Philips prototype suffers relatively more during transients than the ICE). Vehicles controlled to 1975-76 California standards suffer an average fuel economy penalty of 7-10% relative to their 49-state counterparts [55,52], but there is a wide variation in this difference among individual vehicles. Environmental Protection Agency data lists the Ford Torino/Elite with the 351 CID engine at 10 and 16 mpg on the Federal city and highway driving cycles, respectively, at California standards, and 11 and 16 mpg at the 49-state standards [67,68]; this difference cannot be considered statistically significant, so the fuel economy advantage of the Ford-Philips prototype relative to 49-state 1975 vehicles is somewhat unclear. Ford has set a goal of a 35% Stirling cycle fuel economy improvement (over the same cycle and baseline) for their government-sponsored compact vehicle engine design, to be attained with some projected advances in FGS technology beyond the Ford-Philips prototype. The recent report by the Jet Propulsion Laboratory (JPL) [8] has calculated that, without any major technical advances (i.e. using the basic components of our FGS system), an optimized Stirling engine could achieve approximately a 30% efficiency improvement relative to the Ford-

Philips engine;¹ this estimate is questioned by many others in the field. Thus the efficiency advantage of the Stirling engine relative to the 1975 49-state ICE is likely in the range of about 20% to 50%.

In the previous chapter we discussed the relation of the 1985 ICE to the present ICE, indicating that an efficiency improvement of -5% to about 20% might be obtained relative to the present ICE.² Thus the fuel economy advantage of the FGS Stirling relative to the 1985 ICE lies roughly in the range 0 to 55%. In the next chapter we address the impact of this uncertainty on the maximum acceptable initial cost.

Finally, the multi-fuel capability of the engine is clear. Its valuation, however, is very unclear, although certainly positive if considered relative to operation on gasoline (as an option, it obviously has a minimum value of zero; emissions with fuels heavier than gasoline could be a problem). This complicated issue will be addressed in Section 5.3 principally in terms of its impact on the operating economics of the system.

In summary, then, the status of the Stirling engine system may be characterized as follows: laboratory engines have demonstrated on dynamometers the clear potential to attain all the attributes necessary for a marketable system except initial cost; it meets the statutory emissions standards and demonstrates a substantial improvement over the present ICE in fuel economy.

¹The Ford-Philips engine is essentially JPL's "present" engine, the 30% advantage is roughly that which their "mature" engine achieves over the "present".

²The full range was given in Chapter 4 as -15% to +27%, however the upper limit is technically unlikely and the lower limit would require imposition of the 0.4 g/mile NO_x standard at a fuel economy penalty which is probably politically unacceptable.

Initial cost is the principal uncertainty; uncertainties remaining to be pinned down in vehicle testing and further development include maintenance, start-up, safety, durability, and efficiency.

The components comprising this system (our FGS) are individually at a similar status. The system is, however, very complex and presently requires expensive materials and manufacturing techniques for its fabrication. A major development program which would focus on cost reduction while maintaining the other attributes (the Final Development Stage) is necessary before this technology could be developed to the point where a favorable Introduction Decision could be made. There also exist advanced concepts for the Stirling engine which might offer significant improvements in the engine attributes, but it is very unlikely these could be incorporated into a system which could be introduced in the marketplace before the 1990's.

5.2.4 The Heavy Duty Prime Mover Application

Up to this point we have discussed Stirling engine technology primarily in terms of the passenger car application. As discussed in Chapter 1, this is our principal focus; it is where the major social and private benefits are to be found. For two reasons, however, the heavy duty prime mover application is worth a brief discussion: first, there are potentially substantial benefits there (even if they are substantially less than for passenger cars), and second, it could serve as an important stepping stone to the passenger car application. In fact, two of the present Stirling engine research groups, United Stirling and M.A.M. - MWM, are orienting their programs toward the heavy duty prime mover application.

As a parenthetical note it should be pointed out that there are many applications for heat engines - from 1 hp lawn mower engines (ICE's) to 1000 MW (1.3 million hp) electric power generating stations (Rankine cycle systems). The emphasis in government-supported heat engine work (military and space uses aside) naturally is focused on the application where the total usage, (and thus the potential aggregate benefits) are the greatest, even though the Stirling system might yield a greater benefit, per unit of usage, in some other application.¹

Here we are addressing the "heavy duty" application, which essentially consists of those applications now dominated by large diesel engines: transportation by trucks, buses, and ships, and electric power generation units (for industrial plants or small communities). It appears that the maximum thermal efficiency of the FGS will be 3 to 7 percentage points lower than that of the present diesel (32-35% at peak as compared to 37-39%). Thus (FGS) Stirling powered vehicles will be 5 to 20% higher in fuel consumption than diesel-powered vehicles. This deficit would have to be made up by a combination of lower initial cost (with appropriate consideration of engine lifetime) and lower maintenance cost. The baseline in this case, the diesel of the mid-1980's, is likely to (at least) maintain its present efficiency. Its initial cost, already substantially higher than the ICE at the same power, will likely be increased somewhat by noise control requirements (especially in the case of long-haul trucking). The pressure for air pollutant emissions

¹The possibility of special applications can never be eliminated. For example, development of an automotive Rankine cycle engine has been supported by ERDA; ERDA will probably be dropping its support, but the Bureau of Mines is picking the program up for a low-emissions source of power in coal mines.

control on trucks and buses is not nearly as strong as it has been for the passenger car and is less likely to significantly degrade the economics of either system.² Experience has indicated that municipally operated transit systems will not willingly sacrifice any significant economies to obtain reduced emissions or noise, contrary to the hopes of some Stirling engine proponents, and long-haul truckers are even less likely to do so.

In the following section on the economics of the Stirling system we will confine our analysis to the passenger car application. It is not clear at this time, however, that the heavy-duty prime mover application is not a more likely candidate for widespread application of Stirling technology, and a serious study of the relevant economics should certainly be undertaken.

5.3 The Social Economics of Government Investment in the Stirling Engine

In this chapter we will, following the general guidelines discussed in Chapter 3 above, attempt some rough calculations of the benefits which might be expected to accrue to our society, should the government support a Stirling engine R & D program. These expected benefits will then be compared with the likely costs of such a program to see whether such an investment is justified. Our most important conclusion will be that while the benefits could be substantial, they are very uncertain, first in terms of their magnitude in the event the R & D is successful and the Stirling engine is subsequently commercialized (or its commercialization is hastened) due to government investment, and second in the impact of government funds on the probability of R & D

¹It should be noted, however, that Congress is at this writing considering legislation in this area.

success. Thus the actual calculations made here will be only of the grossest sort, designed to illustrate the essential points of the discussion.

We will confine our economic analysis to the FGS Stirling system, for a number of reasons. First, some features of Advanced Systems will undoubtedly continue to be examined with private funds and, if they come to appear sufficiently ready as well as sufficiently attractive, could always be absorbed into any FGS development program. Second, to delay the engine development program as a whole in order to work on Advanced Systems would be to extend the likely introduction date into the 1990's, passing up a decade of potential benefits from the FGS. Third, a key feature of the Advanced Systems, namely the use of structural ceramics, is of a relatively "basic" nature -- most importantly, research is needed to develop new techniques for the processing of these materials. Such research would have broad implications for many areas of technology involving processes at high temperatures, including other heat engines besides the Stirling. This work is clearly deserving of government support, but as discussed in Chapter 3, this type of effort does not need to be justified by the type of economic analysis undertaken here.

Our evaluation of the social economics of government investment in the FGS Stirling will proceed as follows. First, in Subsections 5.3.1 and 5.3.2 the potential benefits of Stirling engine utilization will be examined. The general nature of the proper comparison of vehicles powered by different powerplants will be addressed, some total operating cost calculations made for Stirling-powered vehicles, and the issue of how to aggregate and discount the benefits obtained by many individuals at some distant date will be discussed and some simple calculations presented. In Subsection 5.3.3 the

likely impact of government funds on the possibility of R & D success will be discussed; specifically, the incremental increase in the probability of technical success which might be assigned to the government investment will be assessed. Finally, in Subsection 5.3.4 a set of conclusions will be drawn about the relative costs and benefits of government investment in Stirling engine R & D.

5.3.1 Preliminary Considerations

5.3.1.1 Comparing Future Automotive Powerplants

Within the last few years, numerous studies have attempted to evaluate and compare the alternative automotive powerplants [e.g. 5,7,8,69-71]. Until recently the published evaluations have been mainly qualitative in nature, at best using a scoring system to weigh the various powerplant attributes, and have generally not recognized (or have ambiguously handled) the facts that the powerplants (including the ICE) are now at very different stages of development and must be compared consistently at future dates. In Chapter 3 above we suggested that reduced life-cycle costs of automobile usage, with fuel appropriately priced, was the proper central goal for government-sponsored R & D. Here we will discuss the general features of how these costs should be calculated and, in the process, shed some light on the general deficiencies inherent in any practical calculation technique.

The proper comparison of automotive powerplants can only be made by comparing vehicles designed to utilize those powerplants. In other words, it is not really the attributes of the powerplant, per se, which are of interest either to the consumer or society; it is the attributes of the

vehicle.¹ The attributes of the vehicle are related to those of the powerplant in a complex way, which is subject to considerable design flexibility. For example, the relatively larger vibrational energy output of the diesel or ICE as compared to the Stirling can be compensated for, to provide similar vehicle comfort, by suspension system design, but at a weight and cost premium.

This implies then, that in comparing vehicles having different powerplants, it is crucial to decide the attribute levels to which the vehicles in comparison will be designed. This is not a simple matter. A consumer buys a car because the value of the ownership and operation are to him greater than the cost he incurs, both initially and throughout the ownership period. Therefore, the correct vehicle comparison would be to design vehicles which maximize, for each different engine, the difference between (quantified) value to the consumer and total life-cycle cost. The optimal vehicles for the various powerplants might exhibit very different characteristics due to the differing technological attributes of the engines. For example, the optimal diesel-powered vehicle would most certainly have a lower acceleration than the optimal ICE-powered vehicle, because, due to the lower specific power of the diesel engine, the "cost" of acceleration is higher.

In any case, such an approach is immediately faced with the problem that it is unclear just what consumer to design the vehicle for -- the mar-

¹This statement assumes that, all else held the same, people do not care what the name of the engine under the hood of their vehicle is. This seems a good assumption. However, some evidence to the contrary is provided by the marketing behavior of the automobile manufacturers, such as the use of the labels "Fuel Injection", "CVCC", etc. on some cars. Similarly, for example, it is not hard to imagine a certain emotional appeal to owning a gas turbine-powered car, due to the association with jet aircraft.

ket for automobiles is marked by substantial diversity in consumer "tastes", i.e., the values ascribed to the various vehicle attributes. One element of this diversity which has received much attention is the broad range of sizes (and weights) of vehicles which find willing buyers. The wide range of alternative features which are successfully marketed (even on vehicles of similar size) has received somewhat less attention. The widespread purchase of air conditioning, various forms of power-assisted equipment, vinyl roofs and other decorative features, various engine sizes for a given vehicle size (and thus various levels of vehicle acceleration), etc., indicate the extent and diversity of vehicle attributes valued differently by substantial numbers of consumers. A further feature of the diversity of the automobile market is the widely varying amounts of usage to which consumers subject their vehicle; a recent survey indicated that 25% of vehicle users operate 1-year old cars less than about 5400 miles in a year and 25% more than 17,500 miles (ignoring fleet vehicles). [73] Clearly, these consumers will place a very different relative emphasis on initial and operating costs. Of course, the diverse manner in which these miles are driven are relevant in this consideration as well ("urban" vs. "rural", for example).

It is clearly impossible (even if desirable) to treat the optimization of the vehicles with different powerplants for this market in all its diversity without knowledge of consumer (and societal, if different) valuations of vehicle attributes.¹ A reasonable approximation is to segment the market into a limited number of classes, each one uniform in the set of the most

¹Although an attempt was made by Dewees to estimate the price consumers were willing to pay, for example, for extra horsepower at a given vehicle weight, using econometric techniques on price data for a wide variety of vehicles. [72]

important vehicle attributes, and to choose some appropriate annual mileage (possibly varying with the age of the vehicle). With the assumption that the value to the consumer is the same if these attributes are the same, the problem of determining the optimum powerplant reduces from the choice of the one which maximizes net vehicle value to the one which minimizes total vehicle costs. This has been essentially the treatment utilized by the two most recent evaluations of alternative powerplants, those by JPL and Rand [8 & 7, respectively], where vehicle acceleration (which essentially determines engine size), internal compartment size, tank mileage, and the choice of key power-consuming accessories have been the features held constant within (although different between) a number of vehicle size classes. In these studies vehicles were synthesized, for each powerplant, to attain the specified attributes. In this technique, the "optimal" powerplant is then chosen by looking across the different size classes; the dominance of one or two powerplants is hoped for, and in fact has been found. ¹

A key result of the JPL and Rand studies was that they laid bare the importance of engine specific power (by weight or, less importantly, volume) in determining the relationship between engine efficiency and vehicle fuel economy. All else held the same, a vehicle powered by a heavier engine will have a poorer fuel economy than a vehicle with an equally efficient but lighter engine. The difference in vehicle weights will be substantially greater than the difference in engine weights due to the heavier vehicle

¹It should be noted, however, that if the vehicles within each size class had been optimized for maximum net value, and if the alternative powerplants have significantly differing scalabilities and the vehicles thus had differing accelerations, then different powerplants might turn out to be optimal for the various vehicle classes.

frame needed to support the engine, the consequently higher installed engine power required to attain the same performance, the heavier drivetrain needed to transmit the higher power, larger gas tank and extra fuel needed to maintain tank mileage, etc. The most noticeable impact of this effect was that the fuel economy advantage of diesel-powered vehicles was found to be considerably less than the relatively high thermal efficiency would imply without due consideration given to the diesel's relatively low specific power.

Another important feature of the Rand and JPL analyses was that they determined vehicle fuel economy over a specific driving cycle; very often alternative powerplant comparisons have utilized point estimates of thermal efficiency (usually the maximum), which do not account for the differing variation of efficiency with engine loading. The vehicle synthesis approach to powerplant comparisons also forces the analyst to address the question of differing accessory requirements for the alternatives (larger starter motor for the diesel, larger radiator for the Stirling, etc.); lack of a careful accounting for accessory requirements has been a problem with previous analyses.

One difficulty with this vehicle synthesis approach is that it is likely to be valid only over the long run, i.e. well after the first introduction of an alternative powerplant, when the whole vehicle system has been optimized. As discussed in Section 5.4, an alternative powerplant is likely to be introduced in a vehicle frame close to that already optimized for the contemporary ICE. Thus, while the approach is useful for estimating the long-run impact, it may be less useful for examining the prospects of a favorable Introduction Decision, which would likely be based on the less than optimal attributes of a vehicle using a body designed for the ICE. Similar considerations apply to the type of fuel it is assumed that the alternative powerplants will utilize.

The JPL study, for example, assumed the immediate availability of a broad-cut distillate fuel, at some price advantage, for those engines such as the Stirling which could presumably use it. Like the optimized body, this desirable feature of the future is only likely to be fully realized in the long run, well after a successful introduction has been made.¹

Another aspect of alternative powerplant comparisons is the need for consistent technology forecasts. The concept of the ICE as a moving baseline (as discussed in Chapter 4) is now becoming widely recognized, although analyses still appear comparing future alternatives with today's ICE. When advances in the technologies under comparison are likely to be independent, then each must be separately forecast. Often, however, this is not the case -- in fact, studies of technological innovation have found that advances in a new system tend to be aggressively incorporated into the threatened older system as the economic interests associated with the older system strive to protect it. [74] It is, therefore, very necessary that comparisons made at future dates apply advances in technology consistently. Of direct relevance here is the possible development of high temperature load-bearing components made from ceramics. Most of the relevant development work in this area has been focused on components for gas turbine engines. However, as previously stated, this technology would very likely apply to an advanced Stirling engine and very possibly the ICE and diesel as well, though the impact is different in each case.

Finally, the emissions issue deserves further comment. Regulations for exhaust emissions must be satisfied and we need a framework for evaluating

¹It might be possible to apply these vehicle synthesis tools to the Introduction Decision, using appropriate constraints.

the low emissions potential of the alternatives. This is especially complicated because (as previously discussed) there is short-term uncertainty as to what the emission standards will be; there is uncertainty in the longer-term potential of the ICE for further emissions reductions, and for the ICE and for some of the alternative engines, there are tradeoffs between emission control and fuel economy (as well as initial and operating costs). It is tempting to say that comparisons should be made at the same emissions levels. But this ignores the fact that with the existence of a dominant technology, the ICE, the applicable standards effectively represent what is achievable at some reasonable control cost; that is, an implicit tradeoff between benefits and costs is always present. The different engine technologies, since they have different emissions-level versus cost functions, would presumably achieve the appropriate benefit-cost trade-off at different emission standards. There is no easy way out of this dilemma. We have concluded that, unless the structure of the Clean Air Act is changed, for alternative engines to be attractive they must offer the potential for emissions at least as low as those projected for the ICE over a comparable time frame. Furthermore, because the marginal cost of low emissions levels for some of the alternatives is much less than for the ICE, it may in fact be appropriate to compare them at different emissions standards. Thus, as we will examine later, the Stirling engine could well carry an additional social benefit relative to the ICE, because it can be introduced at lower emissions levels.

5.3.1.2 A Simple Total Operating Cost Model for the Stirling System

In this subsection a simple calculation procedure is developed for comparing the "total operating costs" (defined here to include initial outlay

minus scrap recovery as well as direct operating costs) of the Stirling system with the baseline ICE. We want to focus on the tradeoff between the uncertain, but probably high, initial cost of the Stirling engine, and its superior fuel economy; with the future fuel market prices, the type of fuel to be used by the Stirling, and the properties of the baseline ICE as the crucial unknowns (ignoring other key uncertainties such as maintenance cost differences). The model can be used for making total operating cost calculations as privately or socially perceived depending on the values of the input parameters used. In this section (5.3) we will perform only social calculations, for use in our cost-benefit analysis. In Section 5.4 we will use the same equation to calculate privately perceived costs and the difference between the two will be used there to explore the commercialization issue.

A number of recent investigations have used various calculation procedures for evaluating the impact of vehicle changes on total vehicle costs. [7,8,17,53,76] A series of critical choices have to be made, centering around the issues of appropriately allocating the initial cost over the lifetime mileage of the vehicle, and treating the variation of average vehicle mileage with vehicle age. Our interest here is to examine in gross terms the initial-cost/fuel-economy tradeoff. Therefore, rather than developing a detailed procedure for dealing with the temporal variation of capital and operating charges, we simply use a non-rigorous but intuitively satisfactory procedure which captures the key features of interest. It is most similar to that used by Rand. [7]

We calculate the rough difference in average total cost per mile between the Stirling and baseline vehicles, where the average is both temporal (throughout the vehicle's life) and cross-sectional (over various users and vehicles).

Let:

T = Total annual average vehicle cost;

I = Initial vehicle purchase price;

A = Annualized fraction of capital cost;

V = Vehicle total operating cost other than fuel and capital costs, i.e. maintenance, insurance, oil, etc., all calculated on a per mile basis;

P = Price of fuel (detailed choice will be addressed below);

F = Vehicle fuel consumption per mile;

M = Average annual miles traveled;

C = Total average cost per mile; and

L = Number of years of vehicle life.

Then from the definitions above we calculate C as:

$$C = T/M = (I \times A / M) + V + P \times F \quad (1), (2)$$

We use a single average vehicle lifetime and average annual vehicle mileage, and we assume them invariant over time (for our future comparisons) and between vehicles (e.g. no durability differences). $I \times A$ will be calculated as the amount of a single payment made at the end of each of the L years of the vehicle lifetime, whose present value equals the initial cost of the vehicle minus its discounted salvage value; i.e.,

$$I \times [1 - \frac{\gamma}{(1+i)^L}] = \sum_{j=1}^L \frac{I \times A}{(1+i)^j} \quad ; \quad (3)$$

where:

i = Relevant interest rate; and

γ = Fraction of initial value received for salvage at end of vehicle life.

Thus :

$$A = \frac{i \times [(1+i)^L - \gamma]}{(1+i)^L - 1} \quad (4)$$

Implicit in this calculation is the incorporation of a net cost of capital of interest rate i , with no distinction as to whether this is an opportunity cost of the capital value of the vehicle or a debt financing charge. The initial cost (I) is the total cost of the vehicle, carrying its proportionate share of plant and corporate overhead, dealer costs, profits, and industry R & D investment (i.e. approximately the purchase cost).

We now consider the difference in the total cost per mile (ΔC) between the Stirling and baseline systems, using the subscripts S and B, respectively, and the symbol Δ to be the cost of the baseline system over the Stirling system (i.e. $\Delta C > 0$ means positive Stirling benefits). As discussed above, we are implicitly assuming that all non-pecuniary attributes are roughly balanced and explicitly hold vehicle acceleration the same; then:

$$\Delta C = (A/M) \times \Delta I + \Delta V + \Delta(P \times F) \quad (5)$$

As discussed above, we should treat ΔI and $\Delta(P \times F)$ on a total vehicle basis (as well as ΔV). However, we now make a simplifying assumption based on the known attributes of the Stirling system (as discussed in Section 5.2 above): that the total engine-related weight (i.e. including necessary engine "accessories") for the Stirling system is the same as that of the baseline for any given power level (i.e. weight-specific-power is the same). We further assume that there is no significant difference in torque-speed curves (it is less clear that this is so). It then follows that the vehicle weights are the same (ignoring the difference in fuel tankage requirements), because engines of the same weight will provide the same acceleration. The two

important consequences for our model are: first, that the only difference in vehicle initial costs is the difference between engine costs at the same rated power and, second, the ratio of vehicle fuel economies is equal to the ratio of engine efficiencies (over the relevant driving cycle). This simple model ignores some features of the Stirling system which may in the long-run prove advantageous. However, it provides us with a tremendous simplification by eliminating the necessity for a complete vehicle synthesis and therefore allowing us to deal with engine attributes directly. Furthermore, as will be seen below, other uncertainties, not directly associated with the engine technologies, are so large as to dominate the errors associated with the simplifying assumption made. Thus we will use:

$$\Delta I = -(R-1) \times E_B \quad ; \quad (6)$$

where

R = Ratio of Stirling to baseline engine cost; and

E_B = Baseline engine cost.

We further assume, for simplicity and for lack of data, that the Stirling and baseline engine operating costs (other than fuel) are the same. This is however, an important assumption, as engine maintenance and repair costs (differences in which would be the dominant contributor to ΔV) can be as high as fuel costs, especially in the later years of a vehicle's life. Finally, then, let:

η = Ratio of Stirling to baseline fuel economy;

and thus

$$\Delta C = -(A \times E_B / M) (R-1) + P_B \times F_B (1-1/\eta) + F_B \times \Delta P / \eta \quad . \quad (7)$$

The consideration of the possible Stirling fuel price advantage as a difference in fuel price, rather than a fractional decrease from gasoline, is because the difference would be attributable to refining costs, whereas movements in the price of both gasoline and some other Stirling fuel would be expected to occur principally due to changes in the cost of crude oil. Refining costs are, of course, additive, to and independent of the cost of the incoming crude.

Finally it is useful to define two specific points on the relation given by equation (7). First, let us define R_0 as the "break-even" ratio of Stirling engine cost to ICE cost, i.e. the ratio where the Stirling benefits are zero ($\Delta C = 0$):

$$R_0 = 1 + [A \times E_B / M] [P_B \times F_B (1 - 1/\eta) + F_B \times \Delta P / \eta] \quad . \quad (8)$$

This may be considered a minimal R & D goal, i.e. the (relative) Stirling cost must be less than R_0 for the Stirling vehicle to achieve positive benefits. Second, we would like an upper bound for the benefits to be obtained from Stirling utilization [$(\Delta C)_{\max}$]. Since it is generally conceded that the Stirling engine is likely to be always more expensive than the ICE, we will use the value of Stirling engine benefits at equal costs ($R=1$) for this calculation:

$$(\Delta C)_{\max} = P_B \times F_B (1 - 1/\eta) + F_B \times \Delta P / \eta \quad . \quad (9)$$

As a final note, we will be making our calculations for engine of the future. We will use constant (roughly 1975) dollars, and real interest rates (excluding the effect of inflation).

5.3.2 The Potential Benefits of Stirling Vehicle Commercialization

Before proceeding a brief comment is useful to provide an overview of the benefits analysis, especially in light of the "energy conservation" issue. As discussed in Section 5.2, the Stirling engine will undoubtedly cost more than the equivalent ICE, but it will probably be more efficient, giving Stirling-powered vehicles more miles-per-gallon than their ICE-powered counterparts. The higher initial cost represents an increased consumption of real resources -- expensive superalloys (requiring chromium, nickel, cobalt, tungsten, etc.), increased quantities of tools and equipment to machine the superalloys, increased labor, etc.¹ -- which would be traded principally for reduced petroleum consumption in vehicle operation. The principal potential "benefits" of Stirling vehicle commercialization would be the surplus of the value of the reduced petroleum consumption over the increased consumption of these other resources in the vehicle's manufacture. This is why the Stirling vehicle is of interest as part of our national goal for energy conservation. The principal focus of this subsection will be the issue of how much increased first cost we are willing to trade for the reduced fuel consumption, under various conditions which might obtain in the future and for different prices used in valuing petroleum from a social standpoint, and thus the likely magnitude of the net benefits to be obtained.

5.3.2.1 Single Vehicle Analyses

We now apply the cost model developed in the previous subsection to examine the potential total operating advantage of the FGS-Stirling-powered

¹See [8] for detailed estimates.

vehicle relative to the 1985 ICE. By using the FGS Stirling, which does not employ structural ceramics or any other advanced concepts, we are using a consistent technology forecast. Our calculations are designed to estimate the social benefits; in Section 5.4 we will deal with the possible disparities between the social and private benefits and the implication of these disparities. The parameters we use in our equations will reflect this; the two where this raises obvious issues are the interest rate used in the capital amortization coefficient, and the price of the fuel used by the baseline system (viz., gasoline).¹ We will use a social discount rate which may not represent the cost of capital implicit in consumer vehicle purchase behavior, and a fuel price which is higher, by an uncertain social premium, than the market price. We will include the tax on fuel as part of its market price, since automotive tax revenues are generally spent on road construction and maintenance and thus represent a real part of the social cost of automobile operation rather than a mere transfer payment. For the other prices and other parameters we will use observed values. Only one vehicle size will be considered -- a medium-size vehicle weighing about 3500 lbs. -- and this will be sufficient for our purposes, which are to indicate the rough magnitude of the likely benefits, the social break-even initial cost, and the impact of the key uncertainties.

As previously discussed we will calculate the total Stirling operating advantage as a function of Stirling engine initial cost. We will make this calculation for one "Base Case" (Case 1), and then for three other cases,

¹Since the Stirling fuel price is the baseline fuel price minus a refining advantage, we need only consider the baseline price in this respect.

each of which examines the impact of a single critical unknown.¹ The impact of each unknown is examined through the choice of a single plausible value of the relevant parameter. Table 5.2 lists the parameter values used in the calculations and Table 5.3 and Figure 5.2 show the results. The Base Case represents an FGS Stirling vehicle with a fuel economy about the minimum reasonably assured, relative to our projected minimally efficient 1985 ICE at current emissions standards, both running on gasoline at today's market prices. (This is not quite a worst case calculation for the Stirling as the 1985 ICE would likely be somewhat more efficient than the minimal projection used here, as discussed in Chapter 4). In Case 2 the relative Stirling fuel economy advantage is double that of Case 1. This roughly represents either of two possibilities: 1) the realization of a higher Stirling engine efficiency than that of the present prototype, closer to that of JPL's "mature" Stirling (although the calculation does not account for the possible cost savings due to decreased engine size and vehicle), or 2) the impact of tighter emission controls, such as the current statutory long-term standards (although the calculation does not account for the associated increase in baseline engine cost). Case 3 shows the impact of a substantial (50%) increase in fuel price, representing a large social premium, a significant increase in fuel prices, or a combination of the two. Case 4 shows the impact of the use of cheaper fuel than gasoline; the difference is roughly that between gasoline and diesel fuel today, corrected for differing BTU content and taxes. Actually the Stirling could run on a less restrictive "broad-cut distillate", (and probably would in the long-run if actually commercialized) which would be slightly less expensive than today's diesel fuel. As previously discussed,

¹Case 5 will be discussed in Section 5.4.

Table 5.2

PARAMETER VALUES USED IN STIRLING VEHICLE TOTAL OPERATING COST CALCULATIONS

I. Parameter Values Used in All Cases

<u>Parameter</u>	<u>Value</u>	<u>Comment</u>
M	10,000 miles	Has been rising slowly over past decade. [10,p.44]
E_B	\$900	Retail 150 hp ICE cost (see Chapter 4).
F_B	.04 gal./mi. [25 mi./gal.]	17 mpg (1975 3500 lb. avg. [52]), + 30% non-engine improvement by 1985 [8,p.10-16], plus 15% minimum expected baseline engine improvement (see Chapter 4).
L	10 yrs.	Roughly constant. [17,p.3-11]
γ	.07	[7,17]

II. Parameter Values Used in Base Case

<u>Parameter</u>	<u>Value</u>	<u>Comment</u>
P_B	55¢/gal.	Approximate national average market price of unleaded gasoline including taxes. [77]
ΔP	0¢/gal.	Stirling operating on gasoline.
i	4%/yr.	Social real discount rate (range 3-5%).
A	.12	Calculated from i and γ .
η	1.15	Minimum reasonable FGS Stirling efficiency improvement factor over 1985 ICE. (Minimal expected advantage for Ford-Philips prototype re 1975 Calif. Torino (30%), -5% guess for 49-state Torino advantage over Calif., + 10% minimal FGS gain above Ford-Philips prototype, -15% minimum expected 1985 ICE gain over 1975).

III. Parameter Values Used in Cases 2-5

<u>Case No.</u>	<u>Parameter Differing from Base Case</u>	<u>Value</u>	<u>Comment</u>
2	η	1.30	Arbitrary doubling of Stirling advantage (could be due to better Stirling efficiency and/or tighter ICE emissions standards).
3	P_B	83¢/gal.	50% increase in gas price (due to social premium and/or market price increase).

Table 5.2 (Cont'd)

III. Parameter Values Used in Cases 2-5 (Cont'd)

<u>Case No.</u>	<u>Parameter Differing from Base Case</u>	<u>Value</u>	<u>Comment</u>
4	ΔP	4¢/gal.	Approximate price advantage of broad-cut distillate or diesel fuel over gasoline. [8,p.20-6]
5	i (A)	15%/yr. (.20)	Possible consumer discount rate.

Table 5.3

SUMMARY OF STIRLING VEHICLE TOTAL OPERATING COST CALCULATION RESULTS

Case	Parameter Changed From Base	Break-even Relative Engine Cost [R_0]	Maximum Benefit (¢/mile) [(ΔC) _{max}]
Base	---	1.26	.29
2	$\eta = 1.30$	1.47	.51
3	$P_B = 83\text{¢/gal.}$	1.40	.43
4	$\Delta P = 4\text{¢/gal.}$	1.40	.43
5	$i = 15\%/yr.$ ($A = .20$)	1.16	.29

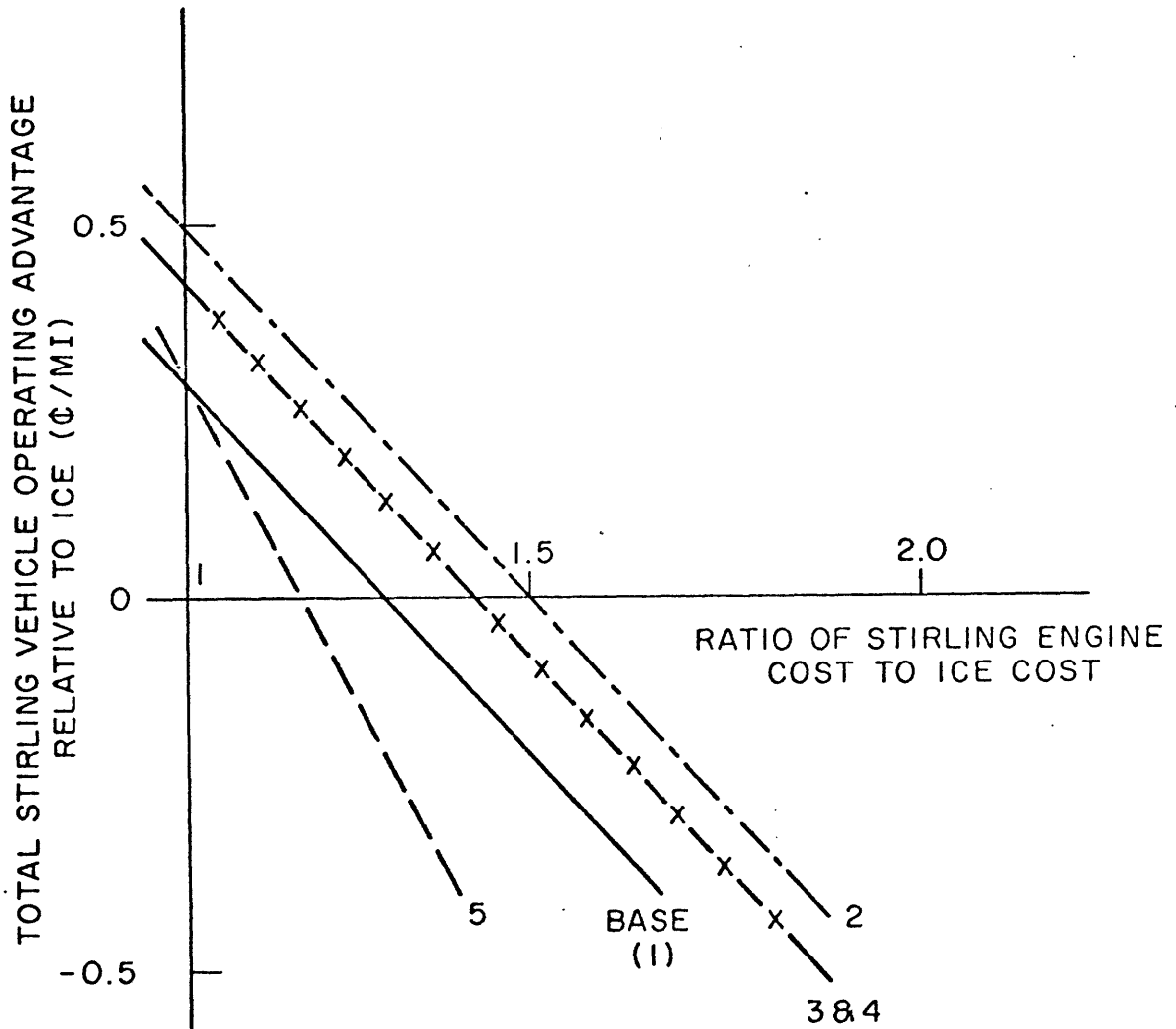


Figure 5.2

STIRLING TOTAL OPERATING ADVANTAGE AS A
FUNCTION OF STIRLING ENGINE INITIAL COST

(Base Case: $\eta=1.15$, $P_B=55\text{¢/gal.}$, $\Delta P=0\text{¢/gal.}$,
 $i=4\%/yr.$; Case 2: $\eta=1.30$; Case 3: $P_B=83\text{¢/gal.}$;
Case 4: $\Delta P=4\text{¢/gal.}$; Case 5: $i=15\%/yr.$)

the only publicly available detailed estimate for the initial cost of the Stirling engine, that of JPL [8] is in the range of 1.2 to 1.7 times that of the equivalent ICE, so that there seems a reasonable chance that it does in fact lie within the range of interest.

In summary, the results indicate that social benefits in the range of several tenths of a cent per mile may result from Stirling engine operation, if the R & D efforts are successful in bringing the engine's cost down to within 20 to 40% above that of the ICE. The impact of the critical unknowns is clear: at an initial cost in the range of interest, the uncertainty in the level of social benefits is of the same order as its likely magnitude, and similarly with the allowable extra cost of the Stirling above the ICE.

We will discuss below the aggregate value of savings of tenths of a cent per vehicle mile, but is of interest here to compare this with the total operating (social or private) cost of the baseline system. Including capital charge, fuel costs, maintenance and parts, tires, oil, insurance, garaging, parking and tolls, and taxes, the total operating cost of our 1985 baseline system will be about 14¢/mile (± 2 ¢/mile, estimated from [76]). Thus the likely social savings due to Stirling engine commercialization is only a few per cent of the total cost (social or private) of automobile ownership and operation.

In the above calculations we neglected any explicit consideration of the air pollutant emissions issue. As discussed in Chapter 3, this issue is very difficult to treat. At the simplest level, the R & D planner can treat the emissions issue as a simple constraint; since the Stirling system will very likely meet the most stringent presently legislated standards, this constraint is met. We can, however, proceed somewhat beyond this.

The impact of future emissions standards entered the above calculations only implicitly, in their impact on the relative fuel economies of ICE and Stirling-powered vehicles. It is reasonable to assume that any Stirling engine actually introduced would meet the present statutory (original 1976) emissions standards because, as discussed in Section 5.2, this can be accomplished with little increase in initial cost and no effect on fuel economy (at least when the engine is run on gasoline). Therefore if the Stirling is introduced under circumstances where it replaces ICE's meeting less restrictive standards, a further social benefit accrues due to the operation of Stirling-powered vehicles.

In the spirit of the preceding calculations, we can very crudely bound the monetary value of these benefits. The National Academy of Sciences has estimated the total annual cost (to society, due to health effects, etc.) of automotive emissions as \$2-10 billion for uncontrolled vehicles. [75] Crudely averaging across the three regulated automotive air pollutants, vehicles at the 1975-76 standards emit about 75% less pollutants than uncontrolled vehicles. Making the (conservative) assumption that the costs are directly proportional to emissions levels (there most likely are decreasing marginal costs at lower levels), then the annual aggregate costs of the emissions of a fleet of vehicles at present standards would be \$0.5 to 2.5 billion. The almost complete elimination of these costs to society would be benefits received if a fleet of ICE-powered vehicles at the present interim standards were replaced by a fleet of Stirling-powered vehicles. These aggregate benefits are difficult to deal with on an individual vehicle basis because they vary strongly with the location of the vehicle; i.e. they occur almost entirely in certain urban areas. About half of all vehicle miles are

driven in urban areas [79]; dividing the above aggregate benefits by one-half of a crude estimate for the national annual mileage (see Subsection 5.3.3) one obtains a social benefit of 0.1 to 0.5¢/mile, associated only with vehicles used in metropolitan areas. Even if the emissions of ICE-powered vehicles are not lowered below present levels, the true value of this social benefit is likely to be close to the lower end of the range indicated.

Two conclusions may be drawn from this extremely crude calculation. First, social benefits due to the low emissions potential of the Stirling may be of the same order as those previously calculated, but are likely to be lower, due to continuing reductions in ICE emissions. Second, if the Stirling system replaces an ICE at higher emissions levels, its social value will be higher in urban areas than in rural.¹ In fact, it is possible that the system might yield positive net social benefits in urban areas but not in rural (although this is unlikely given the magnitude of the benefits due to emissions alone relative to the overall level of uncertainty).

We have attempted to value the low-emissions and multi-fuel capabilities of the Stirling system in simple, quantitative terms. There is, however, a somewhat different point of view which captures some of the subtleties missed in our simplistic approach. Both of these Stirling engine features are options which, under circumstances which might prevail in the foreseeable future, might be valuable.

In the emissions case, the Stirling engine may make possible a viable "two-car strategy", whereby low-emissions, but relatively expensive, passenger cars are required to be used in downtown urban areas. If further reduc-

¹This is obviously true of any air pollutant emissions control system -- including those on present ICE's.

tions in emissions from the ICE prove overly expensive to be imposed nationwide the Stirling system might provide a superior low-emissions vehicle at an extra cost acceptable where the costs of air pollution are the greatest. The market for vehicles in large downtown areas is certainly large enough to support Stirling engine production utilizing the available economies of scale in engine manufacture (i.e. much greater than hundreds of thousands a year). Given the uncertainty in estimates of the costs of ambient automotive pollution and the costs of lowering the emissions of the ICE, the availability of the Stirling engine would provide an option which, while difficult to quantitatively evaluate at the present time, should be considered in the government R & D decision.

A similar argument can be made for the multi-fuel capability of the system. Forecasting the continued availability, to say nothing of the price, of automotive fuels over the next couple of decades, is a tenuous art. The extensive discussion at the present time of the possible development of synthetic fuel may make the availability of the system which is relatively insensitive to fuel properties a very desirable option in future planning. Again, this is difficult to evaluate quantitatively but should be considered.

While the crude numbers we have generated are of interest in themselves, one general conclusion stands out clearly: the break-even initial cost, which can be regarded as the crucial R & D goal for future development programs, is highly uncertain at this time. It depends very strongly on two issues which are presently the subject of intense political debate and are relatively independent of R & D success: automotive fuel prices and air pollutant emissions standards. Fuel prices are also relatively unpredictable

to the extent that they depend on the international market price of crude oil, presently set by the OPEC cartel. It also depends on the type of fuels available, although in the long-run a successful commercialization would induce the availability of low-cost fuel. It depends on the relatively independent fuel economy advances made by the ICE (at a given emissions level). It depends on the (weakly coupled) extent to which efficiency advances can be made beyond the level of the present Ford-Philips prototype. Finally, there may be differences in non-fuel operating costs and durability, which we have ignored. Thus any R & D program is shooting at an unpredictable and moving target.

5.3.2.2 The Aggregate Benefits of Stirling Engine Introduction

In this subsection, we very quickly address the potential aggregate benefits of the introduction of Stirling-powered vehicles. Because the numbers tend to be very large over a range of possible assumptions, we do not expend any effort in calculating more than extremely crude estimates. The calculation is the present value, in 1975, of discounted future benefits, in order to have an appropriate figure to compare with the possible government expenditures on Stirling engine R & D. The calculation is made in constant (1975) dollars, with a real social discount rate (not incorporating the effects of inflation). The key variables in the calculation are: the date by which the bulk of the vehicle fleet is converted to Stirling-powered vehicles, the discount rate, the number of vehicle miles traveled in future years, and the benefits associated with each mile of travel in a Stirling-powered vehicle as compared to one powered by an ICE.

The earliest possible date for introduction of the FGS Stirling is 1985.

Since it is unlikely that, if the Stirling engine were superior in one passenger class, it would not be superior in all, we assume a complete conversion of all engine manufacturing facilities. Such a conversion would likely take ten to fifteen years (ten is usually quoted as the fastest reasonable, e.g. [8]). With an average vehicle lifetime of about ten years, the bulk of the vehicle fleet could be Stirling-powered by about the year 2000. We also use a less optimistic date of 2010.

The amount of private vehicle travel in the turn-of-the-century time frame is the subject of varying forecasts; we assume that it will have grown approximately 50% from the present, to about 1.5 trillion (1.5×10^{12}) vehicle miles, and we assume it constant. The potential benefits from a successful Stirling engine program were discussed in the previous subsection. In 1985 they were estimated to be several tenths of a cent per mile. It is not clear whether they would be expected to increase or decrease as a function of time -- it would depend on the relative technological progress of the Stirling and the ICE, as well as changes in other factors such as the price of fuel. For our crude calculation we assume that ten years of benefits of 0.2¢/mile are obtained. This would roughly reflect an average value over ten years with a fading out of the benefits (or, as will be discussed further in Subsection 5.3.4, it could reflect the fact that only 10 years of benefits could be attributed to a government R & D program, viz., the Stirling would have been introduced in ten years anyway without government R & D). We have previously used a social discount rate of 4%/year, we also test a more conservative 8%/year. The calculation, then, takes the form:

$$B = \frac{\Delta C \times M}{i \times (1+i)^N} \left[1 - \frac{1}{(1+i)^L} \right] ; \quad (10)$$

where :

B = Present value of future benefits (\$);

ΔC = Benefits per mile (\$/mile);

i = Social discount rate;

N = Number of years from 1975 to fleet conversion;

M = Total annual vehicle miles (miles/yr.); and

L = Number of years of benefits.

The results are shown in Table 5.4. They are hardly surprising. First, they show the large impact on the choice of discount rate on the present value of benefits received 25 to 35 years in the future. However, we see that, under reasonable assumptions, benefits having a present value in the billions of dollars are easy to demonstrate.

While in this report we have addressed the issue of energy conservation as strictly a matter of economics, assuming fuel to be appropriately valued in the calculations, it would be useful to look briefly at the aggregate impact of the Stirling engine on fuel consumption. The extent to which the monetary savings discussed here represent fuel savings, of course depends on the particular technical features of any Stirling vehicle commercialized. Any such vehicle would necessarily involve a substantial reduction in aggregate automotive fuel consumption, at least to make up for its higher initial cost. The aggregate annual benefits discussed here are consistent with a fuel savings of from several hundred thousand to one million barrels per day.

5.3.3 Impact of Federal Funding on Stirling Engine Technology

In this subsection we examine the issue of the responsiveness of Stir-

Table 5.4

PRESENT VALUE OF AGGREGATE STIRLING BENEFITS

Social Discount Rate	Years to Fleet Conversion	Present Value of Aggregate Benefits
<u>i (yr.⁻¹)</u>	<u>N (yr.)</u>	<u>B (10⁹\$)</u>
.04	25	9.1
.04	35	6.1
.08	25	2.9
.08	35	1.4

Other parameter values used are:

Stirling vehicle benefits $\Delta C = 0.2\text{¢/mile}$,

Total annual vehicle miles $M = 1.5 \cdot 10^{12}\text{mile/yr.}$, and

Number of years of benefits $L = 10\text{ yr.}$

ling technology to additional financial support; that is, we would like to estimate the incremental increase in probability of Stirling engine commercialization (and thus its associated benefits) due to a given increase in U. S. Government support. We are implicitly assuming, for the moment, that achieving the technical goals (essentially an initial cost providing positive social benefits, as previously discussed), would lead to commercialization; this issue will be discussed in Section 5.4. Stated in general terms, we now address the questions 1) "Would additional support significantly enhance the probability of success (i.e. commercialization) or accelerate the date of success (as compared to ongoing programs)?", and 2) "If so, how much could be usefully spent in this way?"

Before stating the issues in a more formal manner, it is useful to discuss some more general considerations. First, we are dealing here with a technology which is neither "embryonic" nor "mature". As discussed in Section 5.2 above, there have been significant Stirling engine technology development programs underway since 1938. The total cumulative investment to date is certainly in the tens of millions of dollars at least; present programs worldwide involve a total employment of about 230 professionals and an expenditure rate of \$5-10 million annually in three efforts. Complete engines have accumulated many tens of thousands of dynamometer hours, and a sophisticated design and synthesis capability has been developed. The technology remains a dynamic one; as discussed above and in Appendix A, significant advances have been made every few years or so. Furthermore, the incentives for Stirling engine development have significantly increased over the last decade, as the attributes of low emissions and high efficiency have become relatively more valuable. This is reflected in the fact that private-

ly¹ funded development efforts have substantially increased during this period and are likely to remain significant and probably even grow for the next few years at least. Continued technical progress may therefore be expected, even without (U.S.) government funding.

On the other hand, the Stirling engine has not been commercialized in this century.² Thus the engine has never reached the stage where an appropriate organization has felt it to be superior technology for any significant heat engine application. This is very important; as discussed in Chapter 2 above, the potential benefits to be gained by evolutionary advances in systems already in production are usually more apparent to their manufacturers and less risky than investments in commercializing new technology. Thus the R & D investments made in improving the performance and reducing the cost of the ICE, diesel and gas turbine have certainly been several orders of magnitude greater than those on the Stirling.

Because forecasting technological change is such a difficult and uncertain business, these general considerations must weigh heavily in our judgment on the susceptibility of progress on the Stirling engine to increases in funding provided by the U.S. Government. They leave us however, with a very mixed picture.

We will now attempt to be more precise in our analysis. In the following discussion we will utilize the division of Stirling technology into the FGS and Advanced Systems described in Section 5.2, first addressing the FGS.

¹Actually much of United Stirling's program and some of those at Philips and M.A.N. - MWM have been supported by European governments, but we will use "private" here to mean funded by bodies other than the U.S. Government.

²Except for a small number of cryogenic heat pumps sold by Philips.

There are many ways to pose the issue more precisely; here we will start with a relatively simple one: we would like to know the present probability of meeting a specified set of R & D goals by a given date as a function of the annual R & D expenditures. The R & D goals are chosen so that, if they are attained, the Stirling engine is presumed to be commercialized and social benefits are obtained (the benefits of course are a function of the R & D goals). By fixing the date and R & D goals, we have made the benefits of success only implicitly dependent on the R & D investment, and the expected benefits of the R & D investment are the benefits of success times the separately calculated probability of success. Let us ignore the question of changes in annual investment from year-to-year; as will be seen shortly the analysis here will not be detailed enough to cope with that issue.¹ Then, in accordance with the general approach of this chapter, we will crudely subdivide the estimation of the function (defined above) into two parts (more precise expositions of the two questions posed in the first paragraph of this subsection): 1) estimating the general magnitude of the slope of the curve at the present time, and 2) if the slope is satisfactorily high, estimating how much the U.S. Government could usefully spend (before the slope drops off to unacceptable levels).

It seems reasonable to argue that the curve looks something like that shown in Figure 5.3. For expenditures less than B, we do not have the

¹Other ways to pose the question would be to use expected benefits as the dependent variable -- this would include the effect of R & D investment on the probability of success, the benefits of success, and the date of success (the latter through a present value calculation of the benefits), and/or to use cumulative R & D investment as the independent variable, which would make explicit the acceleration of success possible with additional funds (ignoring other limiting factors).

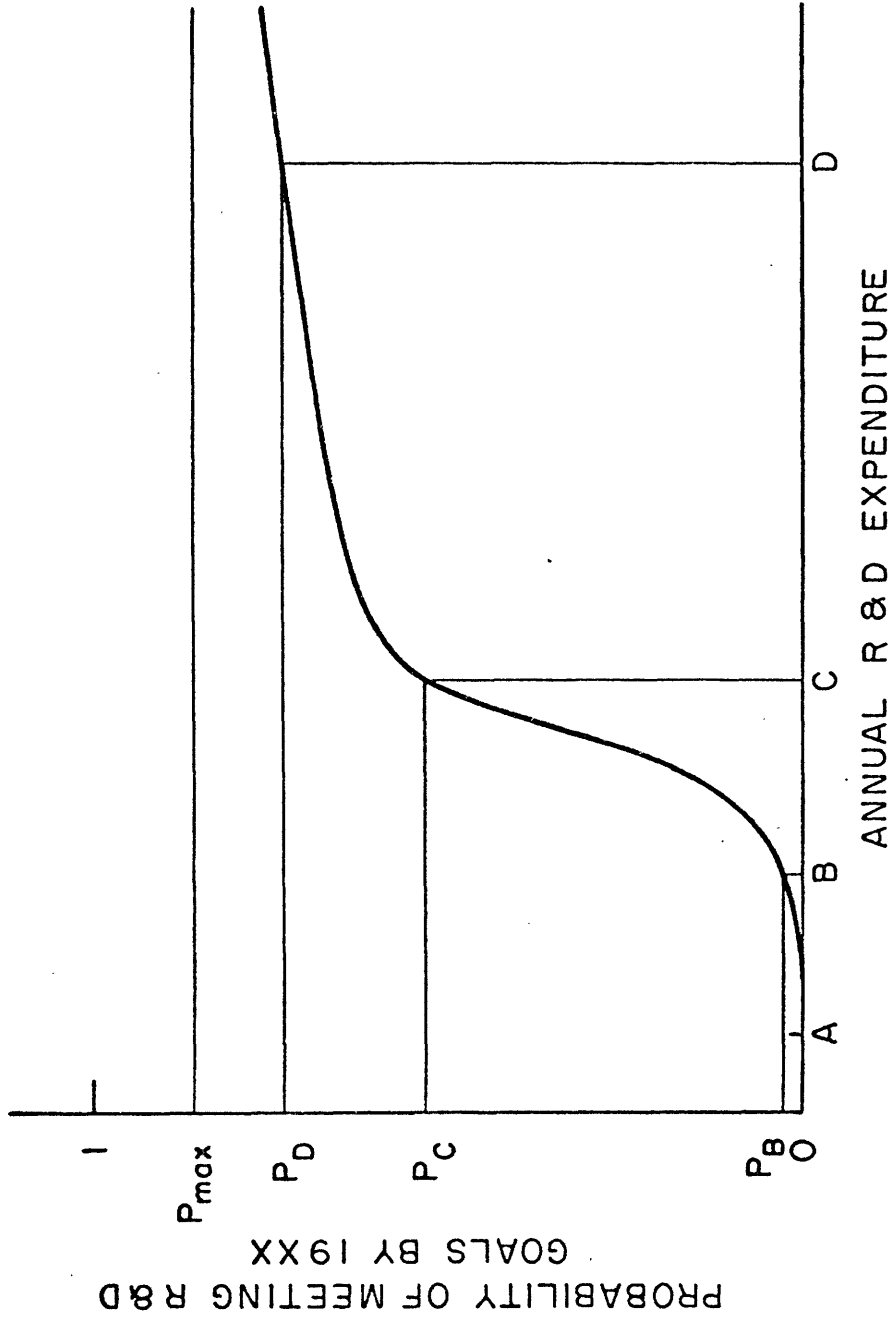


Figure 5.3
PROBABILITY OF TECHNICAL
SUCCESS IN R&D AS A FUNCTION
OF ANNUAL EXPENDITURE RATE

"critical mass" of professionals needed to provide adequate coverage of the relevant disciplines, adequate facilities and support, etc. Thus, for example, if we were at A and increased expenditures to B, we would gain very little. By expenditure level C, however, we have significantly increased the probability of success. At this point no major features or problems of the system are being neglected and no good ideas are being ignored for lack of funds. Beyond C the curve flattens out as further expenditures go toward important problems already receiving attention (with decreasing marginal impact), ideas with somewhat less merit are examined, parallel programs at new groups are started up, etc. Eventually, some limiting probability (P_{\max}), generally less than one (as it seems unlikely that an infinite expenditure rate could guarantee success), is reached.

The magnitude of these probabilities is naturally a function of time, even for the constant technical goals we have assumed. This is because technical success (e.g. a Stirling engine with a certain attribute set) is composed of the success of a time-ordered set of subsidiary goals [e.g. a Stirling engine with a less demanding attribute set by (19XX-3)¹], and the probability of success in 19XX, as seen N years before, is the probability of success in some appropriate subset of those events which have not occurred by year (19XX-N). A crucial distinction must be made between the curve itself, and our knowledge of the curve. Not only does the curve move with time but, probably more importantly, our ability to estimate the curve improves as the technology becomes better understood.

Let us now consider the parameters of the present curve for the Stirling

¹Notation: by (19XX-N) we mean the year which is N years before 19XX.

engine. First, consider only the FGS, and the probability of attaining a satisfactory expected initial cost at the end of the Final Development Stage in 1981 or so (corresponding roughly to the hoped-for Introduction Decision of the present Ford program). In this case the magnitude of the Stirling engine effort worldwide is the relevant expenditure rate.¹ As discussed in Section 5.2 and Appendix A, each major FGS subsystem option is being actively developed by at least one of the ongoing efforts with the focus on simplifying component designs, reducing the amount of expensive manufacturing operations and costly materials necessary, etc., and thereby moving toward a lower cost system. No important concepts which could contribute to the FGS are going unexplored for lack of funds. Thus we are clearly well above point B, probably around C. The total worldwide annual investment is in the range of \$5 to 10 million, supporting about 230 professionals. Adding further to this effort would allow parallel efforts to be undertaken under new programs, allow present efforts to be made more intensive,² and provide for important additional studies (such as the present ERDA scalability study at Ford). By doubling the present effort to D, then, we would expect that the probability of success might be brought significantly closer to P_{\max} from P_C , but the probability of success is unlikely to be doubled.

¹This is an oversimplification because, as discussed in Section 5.2, the major efforts have different goals. In this discussion we will crudely aggregate the relevant expenditures of the different groups. Thus we will also not make a distinction here among recipients of any additional funding, e.g. whether a new effort is started or the Ford effort is supplemented, as long as the expenditure is relevant to the R & D goals considered here.

²A simple example -- by providing additional test engines. Ford estimates the cost of fabricating a fourth unit of the present Ford-Philips engine at about \$500,000.

It is more difficult, however, to judge just what those probabilities are; in fact there is quite substantial disagreement within the technical community. Much of this disagreement is due to the uncertainty in the technical goals and differences between private and social calculations. For our purposes, the crucial technical goal is the attainment of an initial cost which is lower than the social break-even cost (as roughly calculated above) by some "premium" sufficient to obtain the substantial social benefits possible. As discussed above reasonable values of the break-even cost lie in the range of 40 to maybe 70% above the cost of the ICE. For the moment, let us look at the lower bound.

It may well be that evolutionary developments of the FGS will just not be enough to attain an initial cost within 20-30% of that of the ICE, and that, for example, substantial use of ceramics may be required in the heater head to attain a competitive system. Thus P_{\max} may be well short of unity. Estimating this sort of probability is a very difficult task. However, it will be shown that finely tuned estimates are not necessary for our purposes. We estimate P_C to be greater than .1, P_{\max} to be at least twice that, and P_D closer to P_{\max} than P_C . This is given some credence beyond our own judgment by the results of the JPL study, which, as previously discussed, indicates a likely cost premium of 20 to 70%. Given the crudeness of our estimate of the necessary technical goals and the benefits of success, these estimates are sufficient. To the extent that the break-even initial cost is higher than our lower bound, the relevant probabilities are increased. Thus we estimate that a doubling of present worldwide expenditures by the U.S. Government would raise the probability of technical success with FGS technology by at least 0.1. These expenditures would be of the order of \$10-20

million annually for the next year or two, probably doubling through 1981 as the later stages of Final Development are approached, totalling \$100-200 million over six years. We note, however, that the estimation of these probabilities is extremely crude; in the next subsection we will attempt to get around this difficulty by turning the question around and asking what incremental probability would be required for a benefit-cost ratio of unity.

Up to this point we have discussed the probability of meeting the specified technical goal by a given date as if the only alternative were not meeting the goal at all. This is, of course, not the case -- government funding may simply advance the date at which the technical goals are met. A more detailed analysis would obviously be required to take this consideration into account -- more detailed than justified by the large uncertainties and judgemental estimates used. We only note that the length of time saved by a doubling or tripling of funding is, if we are at all close in our estimates of the shape of the curve and the rough placement, likely to be of the order of the number of years from present until the postulated goal, i.e. 5 years to a decade.

Application of the above treatment to Advanced Systems is inherently more difficult as we are by definition attempting to look deeper into our rather cloudy crystal ball, and it therefore will not be attempted here. Advanced concepts are receiving only a fraction of the present expenditures, but they may in fact hold the key to a Stirling engine program which is successful in the longer run. Since they are in an early stage of development, it is likely that they will be relatively responsive to increased funding, and relatively modest additions to the current investment rate appear to be attractive in this regard. At a minimum it is important that

advanced concepts be carefully analyzed to determine their potential impact on the engine's attributes, especially its initial cost. With the current concentration on the FGS in present programs, this may not be taking place to the appropriate extent. It can be expected that the FGS efforts will suggest presently unknown advanced concepts, and these, of course, must be considered as well. A special note should be made of potential developments in the area of ceramic components. The development of the capability to manufacture satisfactory high temperature load-bearing components from ceramic materials would have wide implications for other heat engines besides the Stirling and should be considered in that broader context.

5.3.4 Some Preliminary Conclusions Concerning the Costs and Benefits of Government Support of Stirling Engine R & D

In the preceding subsections of Section 5.3, we have analyzed, and attempted to estimate crudely, the social benefits which might be obtained from widespread replacement of the ICE by the Stirling engine, and the likelihood of the R & D success which would make such an engine a reality. We assume for this cost-benefit analysis that a socially beneficial engine would be commercialized; we will address this issue in the following section.

We need hardly repeat here the uncertainties and complications such calculations have involved and the crudeness of our simple estimates. As discussed in Chapter 3, cost-benefit analyses can be made to any degree of complexity that the available data justifies. In this case we will fold all the compounded probability distributions for the various outcomes into simple point estimates. Our simple criterion is:

$$R = P \times B / C \quad ;$$

(11)

where :

R = Benefit-cost ratio ;

B = Benefits (\$, present value);

P = Probability of obtaining benefits; and

C = Costs (\$, present value).

With this simplest of criteria, any proposed project is accepted if $R > 1$.

We have estimated that social benefits in the range of \$2-9 billion could be obtained by a U.S. Government investment of \$100-200 million, with a probability of at least 0.1. With these numbers we obtain an $R > 1$, possibly up to 10. As discussed above in the relevant sections, these gross estimates apply whether the fact of introduction of the Stirling system is assumed to be attributed to the government, or whether it is assumed that the government investment hastened the introduction by five to ten years.

The most uncertain of the estimates is the probability of technical success. It is useful therefore to turn the criterion around, and estimate the minimum probability which would be required to justify the estimated government investment viz. C/B (i.e. assume $R=1$). The numbers here indicate that the benefits, given success, are one to two orders of magnitude greater than the costs. Thus a probability of technical success in the range of .01-.1 is all that is necessary to provide a reasonable justification for this government investment. A probability at least in this range seems very likely. Looked at this way, investment in the FGS Stirling R & D is a very good gamble for the U. S. Government.

5.4 The U.S. Government in the Process of Automotive TD&P for the Stirling Engine

In the previous section we examined the economics of the Stirling engine as perceived by our society as a whole. As discussed in Chapter 3, however, there very likely are real discrepancies between such social calculations and those of the real decision-makers -- the consumers and manufacturers of automobiles. The substantial benefits potentially available to society from Stirling engine utilization will probably never be obtained unless one or more of the Big Three decides it is in its own best interest to carry the Stirling system through the TD&P process. Of course, the technology may not prove to be even socially beneficial -- only time and further R & D will tell -- but there may be discrepancies between the private decision-making and the social interest which would cause a socially beneficial engine to be rejected at one of the decision points. The fact that only one of the Big Three is presently conducting Stirling engine R & D (i.e., has made a positive Selection Decision) is a good indication that this is in fact probably the case (it is also possible that analysts at GM and Chrysler have different opinions concerning the potential for cost reduction than ours and Ford's).

In this section we will explore some of these possible barriers to commercialization. Since the subject of this report is government-supported R & D, our discussion of possible government intervention in the marketplace will be primarily concerned with R & D, but we will also comment on other possibilities. First we will discuss the likely process by which a Stirling engine would be introduced into the marketplace, addressing the potential barriers inherent in the TD&P process discussed in Chapter 2. Then we will

discuss several possible discrepancies between private and social economic calculations which, even in the long run, could keep a socially beneficial engine from the marketplace. Third, we will address the general implications of these discrepancies for government R & D decisions. Finally, we will make some specific comments on the potential relationship between the U.S. Government and the Ford Motor Company concerning Stirling engine R & D.

5.4.1 The Stirling Engine in the Industry TD&P Process

In Chapter 2 we discussed the process by which the automotive industry would likely make a major technological change. Here we will apply some of that discussion to the possible transition to the Stirling engine. We will concentrate on the Introduction Decision and the Introduction Stage; these are the focal points of the TD&P process -- the preceding development decisions and stages are aimed at a successful introduction, the subsequent stage is easily managed once a successful introduction has been made. As we have discussed in Chapter 3, any government development program must carefully align itself with the industry's TD&P process. To not deal with this process effectively would be to invite failure, in the form of a terminal "demonstration" of a prototype vehicle which would never make it into the Big Three's showrooms. As in Chapter 2 we will include here the government's present intervention in the market; thus this subsection will provide a sort of "baseline" against which the possible further government involvements, discussed below, can be assessed.

If one of the Big Three were to make a positive Introduction Decision with respect to the Stirling engine, it would imply an unmistakable corporate

commitment to success; the magnitude of the expenditures involved are such that the profits in subsequent years could be noticeably affected by a failure of the venture. Estimates of the cumulative prior development investment are on the order of \$100 million, the cost of the Introduction Stage itself, including the first Stirling engine plant, are on the order of \$500 million. Given this total change in the most important of automobile subsystems, the probability of failure at introduction cannot be reduced below a significant level. Thus, the magnitude of the possible dollar loss on a Stirling engine introduction would at least be comparable to that risked on a major new vehicle line,¹ but in a type of venture where the industry has less experience.²

In general terms, Chapter 2 above discussed the criteria the industry has used in the past for making technological changes in its products. Roughly speaking, an innovation had to at least match every relevant attribute (except cost) of the system it replaced. A cost increase would only be tolerated as justified by the net gain in the other attributes. As discussed in Section 5.2 above, the FGS Stirling system has the potential to be comparable or superior to the ICE in every non-pecuniary attribute except possibly start-up time and "apparent" safety, and uncertainties remain in maintenance requirements and durability. Its fuel economy will be substan-

¹White [12, p.74] estimates that Ford invested \$250 million (then current dollars) in the Edsel in 1954-6, eventually losing about \$100 million.

²An automobile industry spokesman recently gave the following assessment: "The great majority of automotive vehicle owners and users really do not care what kind of powerplant is used to accomplish these objectives. They are interested in results, not means or processes. Unless, of course, their powerplant requires more care, greater maintenance, costs more or is less reliable. If any alternative powerplant, although in its early stages of use, departed in any way from previous user experience or even expectation, negative customer response would be immediate and, from the standpoint of private enterprise, retribution would be swift". [78]

tially superior to the present ICE, but how it will compare with the contemporary ICE depends heavily on developments of the ICE. It will most certainly have an initial cost higher than the contemporary ICE. At the time of the Introduction Decision, the economics of the manufacture (i.e. the initial cost) and operation will be well known. The principal criterion for a positive Introduction Decision will be an initial cost (including, of course, an appropriate (for the risk) return on R & D and other capital investment) which consumers find attractive. The principal risks will be associated with the consumers' evaluations of the system, and the government's potential reaction to the availability of the engine.

The crucial feature of a Stirling introduction is that it would take place in an environment which is still dominated by the ICE. While it is possible that some modified form of the ICE (such as the stratified charge or Wankel), or possibly the diesel, may penetrate to some fraction of the new passenger car market by the mid-1980's, the infrastructure for supporting the automotive fleet will be essentially the one in existence today. The first year's Stirling engine production would likely amount to several hundred thousand units; even if the system were very successful and more than one of the Big Three were involved in a massive production conversion program, it would still be several years at least before more than a few percent of the in-use automotive fleet were Stirling-powered. The key components of the infrastructure not in the control of the manufacturer, namely the independent garages and the petroleum industry, would have little incentive to make significant investments to provide materials or services unique to Stirling-powered vehicles -- until either the number of such vehicles on the road were significant, or they had some prior guarantee that such invest-

ments would be profitable (i.e. that the Stirling system was likely to remain in production). In general, then, it is likely that some of the long-term advantages of the Stirling system would not be available to (and some short-term disadvantages would be present for) early purchasers of the system, due both to lack of infrastructure and to design choices made by the manufacturers. This may be very important because the long-run commercial success of the system will very likely be determined by sales during the first few years in the market.

The choice of fuels for Stirling vehicles may be one important example of short-run sacrifices in the Introduction Stage. Stirling engines can operate on less expensive fuels than gasoline, and a given vehicle designed to operate on gasoline will probably be able to run on diesel or a light distillate fuel without any significant problems. As discussed in Section 5.3 above, this could be translated into a real advantage of about 0.1-0.2¢/mile in operating cost. However, today diesel fuel is much less widely available than gasoline so that, unless significant changes are made in the automotive petroleum product distribution system before the Stirling introduction date, many, if not most, Stirling vehicles would be operated on gasoline. If, on that basis, the Stirling system proved itself a success and the number of Stirling vehicles on the road began to grow at a significant rate, then the petroleum refiners and distributors would have the incentive to offer more widely some less refined fuel at a lower price. At first, primarily the distribution system would be affected, as the actual consumption levels would be relatively small due to the small size of the in-use Stirling fleet. Later, significant changes in refinery output would be required and the fuel cost structure would be affected. Speculation as to the national liquid fuel

system in the 1990's is probably not useful here. The crucial point is that the commercial success of the system might well be determined by systems using only gasoline.¹

As discussed in Chapter 2, the industry would attempt to minimize the fixed cost of any innovation. In particular, the investment in related changes to the vehicle body or other key subsystems (such as the transmission) would be avoided to the extent possible. Thus, it is likely that the Stirling engine would be offered in a vehicle body designed for the ICE. Development of a special body for the Stirling vehicle would add considerably to the aggregate investment risked on the Stirling system, probably without significantly decreasing the probability of failure due to the necessary compromises. The Ford-Philips program has demonstrated the "packagability" of an engine which matches the power of the system it replaced (i.e. that its specific power is not significantly worse). This is in notable contrast to a number of the other alternatives which have significantly lower (e.g. the diesel) or higher [e.g. the Wankel, or the gas turbine (at least as analyzed by JPL)] power densities than the ICE. These engines would require significant vehicle redesign or would be offered initially in less-than-optimal configurations. No such compromise would likely be necessary in a Stirling introduction. Other aspects of "integrability", such as vibrational energy output and transmission requirements, make it likely to be suitable for contemporary vehicle bodies and most other key systems.

The provision of adequate service support would require a major invest-

¹It should be noted that the use of a fuel heavier than gasoline raises issues of unregulated air pollutants (particulates, odor, sulfates) similar to those now inhibiting the widespread introduction of the diesel.

ment by the innovating firm. This would include the training of mechanics, stockpiling of replacement parts, etc. at dealerships. The most important feature of the effort might be an assurance to vehicle buyers of adequate service over the vehicle lifetime, even in the event the system is withdrawn from the market. This might require a lengthening of the usual warranty period, or possibly including some unique features in the warranty agreement. Again, however, if the introduction were successful there would probably be no problem, as the independent service facilities would soon compete for the business. Requirements for emergency service, special lubricants, etc., would also have to be considered by the firm introducing an alternative powerplant.

There has been considerable discussion of the industry's ability to finance the transition process -- the key issue being whether depreciation plus retained earnings and any external financing would cover the new tooling plus the capital loss of obsolete equipment. One analysis has concluded that the industry in the aggregate could finance even an unrealistic and expensive 4-year production conversion. [17] The Big Three have argued that government-imposed vehicle changes have absorbed much of their financial capacity for the next few years, and indicated large differences between their abilities to finance more major changes.¹ A successful introduction however, would presumably provide reasonable incentives for further change.

An important feature of the Introduction Decision as it is likely to be made is that, to the ordinary forecasting and business risks of the sort which

¹See the comments by the Big Three in response to this question from Senator Magnuson. [79, pp. 284ff] Chrysler especially might have difficulties because its ability to obtain external financing is presently limited.

industry has previously dealt with, a whole new set of risks have been added by the involvement of the Federal Government in the automotive industry. Nearly every year for the past eight years or so, industry officials have had to justify their alternative powerplant programs to Congressional committees, in the face of hard questioning and potential intervention. This has naturally reflected a national desire for technological change in an industry whose products have a large impact on society. However, from the businessman's point of view, the government's reaction to technological development is a hard-to-predict variable which must be incorporated into his decisions.

A major government involvement in the Introduction Decision is already to be found in the Clean Air Act. Without a change in the structure of the Act, it is too blunt an instrument to directly cause a positive Introduction Decision. This is because (as discussed in Chapter 3) there is virtually no provision for the gradual phase-in of a system whose emissions are substantially lower than those of the contemporary ICE. If the ICE has met a set of standards which appear to be relatively stable, then the Stirling system would be judged against the ICE at those standards; to the extent that the attributes of ICE-powered vehicles have deteriorated due to the standards then a positive Introduction Decision is more likely (as seen in the calculations shown in Section 5.3). If, however, the technology for the ICE to meet stringent standards, such as those readily attainable by the Stirling, were judged "unavailable" and the other attributes of the Stirling were not sufficiently relatively attractive, then a major structural change would be required in the Clean Air Act to bring about lowered emissions through Stirling introduction. Because of the relatively unattractive Stirling attributes (in this scenario),

privately perceived, one or more techniques for changing the privately perceived attributes would have to be utilized. It is possible that the government would exert some sort of pressure to force an extraordinarily rapid conversion to the alternative. Anticipation of such a possibility certainly cannot serve as encouragement to the manufacturers in taking the major risk of introducing an alternative powerplant.

While these issues are important, the dominant criterion in the industry decisions involving the Stirling engine, however, is what it will cost relative to what consumers would be willing to pay for it. This, then, leads us back to questions of the disparity between the socially and privately perceived benefits of the engine.

5.4.2 Private Calculations of Stirling Vehicle Economics

In this subsection we will examine the possible economics of Stirling-powered vehicles from the point of view of the car buyer and manufacturer. Consumers' evaluations of the economics of the Stirling system are inherently difficult to address because, as discussed in Chapter 2, the demand for new cars is volatile and hard to predict, especially as it responds to technological changes. This volatility makes analysis of the attractiveness of low fuel consumption, the Stirling's principal advantage, extremely difficult. The industry's widely publicized improvements in the fuel economy of model year 1975 and 1976 vehicles and the billions of dollars they have stated they are investing over the next few years in fuel-economy-motivated redesign are dramatic. But given the type of demand discussed above the consumers' likely response remains unclear. Analysts [e.g. 7,17,53 and ourselves below] have used various models for computing the privately perceived tradeoff between

operating cost and initial cost, based on various sorts of rational consumer models, for operating cost savings whose total is of the same order as the cost of a vinyl roof. Even with such models it is unclear whether the new car buyer, who typically keeps the car for only several years, is willing to pay for a vehicle life's worth of savings or merely his several years' worth; it depends on how the fuel consumption affects the resale value of the car. To some extent these considerations reflect the dilemma, discussed in Chapter 3, that small reductions in cost, such as those discussed here, aggregate to major social impacts. They also reflect the fact that the American car is bought in part on an emotional basis with its symbolic and aesthetic features possibly more important to the owner than its detailed technical attributes.

In spite of these concerns, we will here proceed to address quantitatively, by simple example as in Section 5.3, the impact of two possible areas of social-private disparity on the consumer's evaluation of the total operating economics of a vehicle. Again we focus on initial cost as the crucial variable; we will take R_0 , the break-even initial cost (initially defined socially in Subsection 5.3.2.1) to represent the maximum initial cost of a Stirling engine which would be acceptable to the consumer. Presumably this is closely related to the decision criteria in the industry TD&P process; whether this is so will be discussed below. Actually, of course, the Stirling's entire attribute set would be considered in such decisions; even within our simple vehicle total operating cost model the attribute pair (R_0, η) determines whether there are net benefits (private or social). Our focus on initial cost is used principally for illustrative purposes.

It is most likely that even a "rational" consumer uses a capital charge,

or interest rate, which is higher than that desirable for society as a whole. For example, the real annual interest rates on new car loans ranged from 2.4 to 8.6% during the period 1971-4 [8, Table 20-7]. This might be considered the appropriate rate for a rational person; whereas, for a number of reasons, real social discount rates are generally considered somewhat lower, in the neighborhood of 3-5% annually. However, there has been considerable speculation that a new automobile buyer simply does not place an appropriate value on operating savings realized years after the initial purchase, probably by a subsequent owner, and thus implicitly uses a higher discount rate than even the rational model would predict. There have been no good studies of this question (such as an econometric study to determine the car buyer's implicit discount rate), but the argument may have merit.

In Case 5 of our total operating cost calculations, shown in Table 5.3 and Figure 5.2, we show the results of such a possibility. Case 5 is identical with the Base Case except that a real annual discount rate of 15% was used in the capital charge calculation, as compared with 4% in the Base Case. The results are clear; under our simple assumptions the tolerable Stirling engine premium over the ICE is reduced from 26% of the ICE cost to 16%. A consumer calculating his costs this way, and an industry basing its decisions on such consumer calculations, would require a substantially less expensive Stirling engine than would be socially beneficial for positive TD&P decisions.

The impact of a positive social premium on fuel on consumer calculations is similar. As discussed in Chapter 3, it is likely that fuel is not (and will not be) priced at its real social value. For example, the value to the nation of reduced imports, beyond the actual cost of the fuel saved, is not

reflected in its market price. Similarly, as long as the market price of motor fuel is determined by some average cost of crude oil, including price-controlled domestically produced crude oil, rather than the marginal cost (which is the cost of imported crude) then there is a disparity between the social and market values of motor fuels. (This may be considered an externality: the gasoline purchaser causes the import of expensive foreign crude, raising the average price of refined products to all consumers of petroleum products.) The impact of such a disparity can be seen in the difference between the Base Case and Case 3 in Table 5.3 and Figure 5.2, using a different interpretation than was used in the discussion in Section 5.3. In Case 3 the price of fuel was taken to be 50% higher than in the Base Case. If the market price of gasoline were 55¢/gal. and the social premium 28¢/gal., (undoubtedly a high estimate), then the Base Case would represent a private calculation and Case 3 a social calculation. Again the impact is clear: the consumer would demand an initial cost of the Stirling engine no greater than 26% higher than that of the ICE, whereas social benefits would be obtained with a Stirling costing no more than 40% more. Again a more stringent criterion is placed on the outcome of the R & D process than would be socially desirable.

The case of air pollutant emissions is the most obvious; if the Stirling vehicle has lower emissions than the contemporary ICE, this would be a socially valuable attribute (at least in urban areas) which consumers would not consider in their vehicle choices.

The possible disparities between social calculations and those made in industry are as difficult to evaluate as those of new car buyers, given the lack of applicable economic theory on oligopoly behavior. In particular the

automobile industry must deal with the impact of new technology on government regulation (and vice versa); how they incorporate this into their decision-making process is unclear. Clearly, distortions in consumer economics, such as those discussed above, are incorporated directly into industry decisions, as the manufacturers obviously will not introduce a vehicle that the public will not buy. Thus the crucial decision criterion, the Stirling's initial cost, will have to be lower than the socially beneficial break-even cost due to the factors discussed above.

It is likely that the actual decision criterion would be even lower than the privately-calculated break-even cost. Clearly the new vehicle must offer a private operating advantage relative to the ICE, and this advantage must be large enough to make the firm confident that the vehicle will in fact sell. Thus the manufacturer would calculate the private break-even initial cost and then subtract off a risk factor. How large this risk factor would have to be is unclear. (It should be noted that the risk involved in investment in the Stirling system would also have been separately considered in the capital return the manufacturer would include in his initial cost calculation.)

It is worth briefly discussing a further implication of a social premium on automotive fuels (there are of course, many other implications outside of the realm of TD&P, such as on the extent of vehicle operation).¹ If there is a significant tradeoff between first cost and fuel economy, then the private firm, optimizing an engine to minimize the total private cost of automotive

¹Another feature of a positive social premium on energy (in other forms as well as automotive fuels), is that the energy consumption involved in engine manufacture becomes a socially relevant figure of merit along with life-cycle cost. We will not address this issue, principally because, as is well known, the operating energy consumption of a passenger car is far greater than that of its manufacture, maintenance, and sales. [7,80]

travel, will choose a design which has a lower initial cost and higher fuel consumption than the socially optimum engine. This is shown clearly (although crudely) in Figure 5.4, where the total fuel consumed in a year's driving (10,000 miles) is plotted against engine initial cost. Let point α represent the position of the ICE in 1985. Line P is a line of constant total private cost of driving 10,000 miles (i.e. the total annual cost on line P is equal to that of using the 1985 ICE). Let curve T represent the Stirling engine technology available for introduction in 1985. It represents the end of a privately successful Final Development Stage, because, at its (private) optimum design point (β), it matches the private total costs of the ICE (except for the risk factor). It demonstrates a distinct initial cost-fuel consumption tradeoff. Line S_1 is a line of constant total social cost, with that cost associated with the ICE (since it passes through α). The lower slope of line S_1 as compared to P is due to the assumed social premium on automotive fuels. Line S_2 indicates the lower social cost of the firm's Stirling engine design (at point β) as compared to its ICE. However, the socially optimum design point is at γ , and, due to the social premium, the potential social benefits associated with the difference between social cost line S_2 and S_3 are not obtained. This simple exercise demonstrates the subtle effects of improper fuel pricing.

5.4.3 Government Involvement in Advancing the Stirling Engine in the TD&P Process

In this subsection we will proceed to discuss some details of the government's possible involvement in the process of automotive TD&P for the purpose of advancing Stirling engine technology. We will address the uncertain-

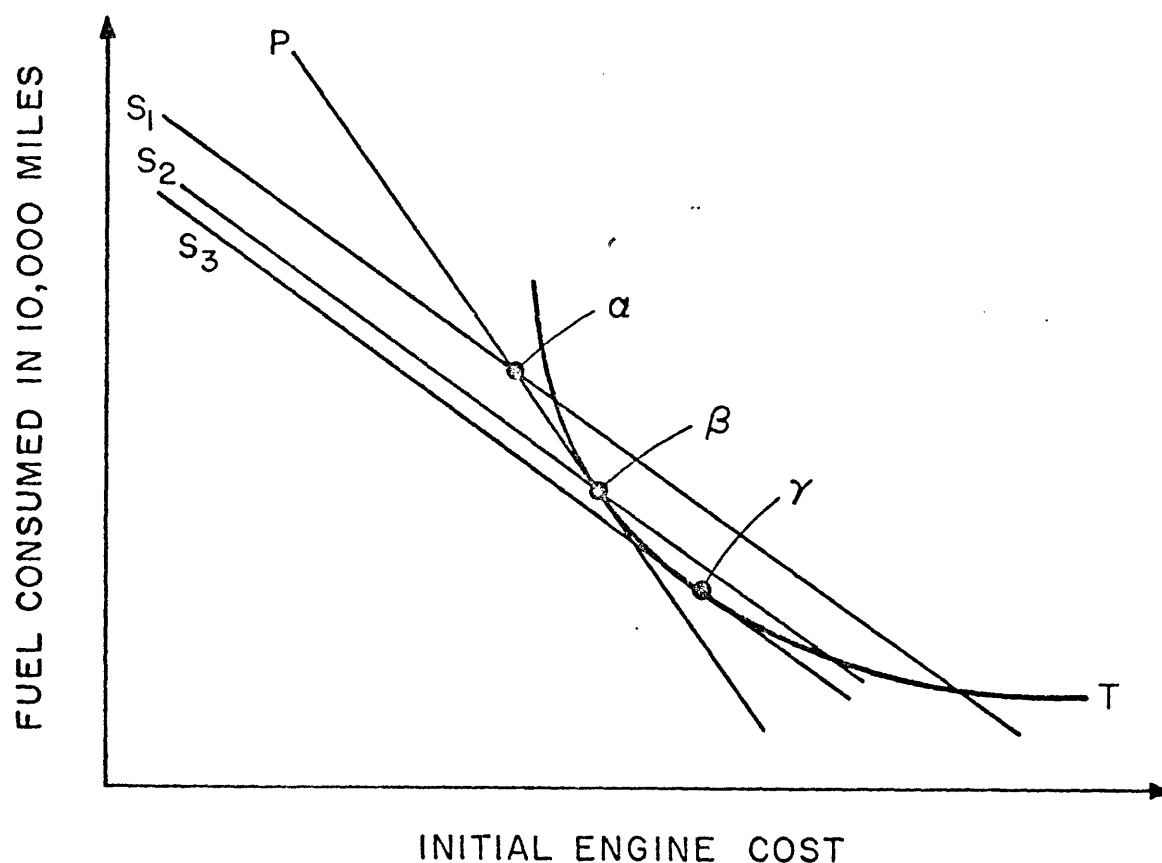


Figure 5.4

IMPACT OF SOCIAL FUEL PREMIUM ON ENGINE DESIGN

(Line P is a line of constant private total operating cost. Lines S₁, S₂ and S₃ are lines of constant social operating cost (with a social fuel premium). Curve T is the available alternative powerplant technology. α is the relevant ICE design point; β is the privately optimal alternative engine design point; and γ is the socially optimal alternative engine design point.)

ties inherent in any such program and possible mechanisms for dealing with the disparities between social and private calculations regarding the utility of Stirling technology. First, the government's general review procedures and decision criteria for an R & D program will be addressed. Next the type of organization which should be used to conduct the R & D work is discussed. Then the inherent limitations of R & D support as a mechanism for aligning social and private incentives is addressed, and the discussion is therefore broadened for a brief set of comments on other ways in which the government might want to intervene in the automotive market to promote major fuel-conserving technological changes such as the Stirling engine.

As discussed in Section 5.3 and previously in this section, the economics of the FGS Stirling system are highly uncertain. The government's R & D programming system must be specifically designed for flexibility in order to accommodate new information as it is developed. The uncertainties may be broken into two categories: first, the technological uncertainties of the Stirling engine itself, i.e. the system's initial cost (and, to a lesser extent, its fuel economy and other attributes); and second, all the other uncertainties -- future domestic fuel prices (as determined both by world crude oil prices and domestic fuel price policy), advances in ICE technology, and future emissions standards. The technological uncertainties are primarily concerned with the actual cost of the system; the others determine the decision criteria for that cost, both the social criterion and the private one. The Stirling's technological uncertainties can be resolved by the investment of funds in development of the engine. Some of the other uncertainties will be resolved with time, some will not. Thus it seems clear that any Stirling R & D program would have to be conducted under a carefully monitored periodic

(presumably annual) review, with the economics of the system assessed each period in light of new knowledge gained in every area. As discussed in Chapter 3 and above, the economics would have to be evaluated from both a social and private standpoint. At some point it might become clear that the cost of the Stirling could very probably not be reduced enough for the system to be even socially beneficial, given the state of the technology and the (then estimated) social decision criterion (essentially the social break-even initial cost). Then the program would be terminated and the government would have lost its bet. Similarly, it might become clear at some point that the initial cost could be easily reduced to the point where it met the industry's private criterion. At that point the industry would (by definition) proceed without further government involvement. In this case substantial social benefits would likely be obtained, because the industry's decision criterion is, as previously discussed, likely to be significantly more stringent than the social criterion.

Clearly the most difficult problem would occur if it appears that the system will be socially beneficial, but will not meet the private criterion. As we have discussed this could very well occur if the government fails to take measures to align the social and private criteria, viz. change the structure of the Clean Air Act, price fuel at its social value, or other possibilities discussed below. In this case there is little point in proceeding with the program. Even if the government continued support through production, no one (or at least very few people) would buy the vehicle.

How should the government-supported program be organized? At this point the Stirling system is late in the Initial Development Stage. The competing concepts for the various components are being sorted out; the emphasis world-

wide is shifting to cost reduction through improved design. Since initial cost is the crucial factor which will determine the ultimate success or failure of the system, it is important that government-supported work be carried out by organizations whose primary incentives are in this direction and which have proven capability in this area. Such organizations are, of course, only in the automotive industry, i.e. the Big Three and their component suppliers.

Furthermore it is very important that the work-performing organization have a stake in making the system a commercial success. Thus a cost-sharing arrangement would be the most desirable form of agreement. A cost-sharing agreement with one of the Big Three would insure not only that cost was emphasized, but also that all those other factors -- pleasability, serviceability, etc. which are so important to commercial success -- would be given adequate attention. As long as one of the Big Three is investing its own funds in the project, it is signalling its evaluation that the (private) Introduction Decision criteria have a reasonable likelihood of attainment. As discussed above, attainment of the private criteria (which would include government interventions actually extant) is necessary for success.

This discussion refers to work on the FGS Stirling only. Advanced Systems, on the other hand, could be well pursued by government laboratories or by non-automotive firms interested primarily in R & D (rather than commercialization) with direct grants. Of necessity such work would overlap and require close interface with FGS programs.

However, government support of R & D is very limited in its ability to correct market failures more basic than underinvestment in R & D. Although it might affect the Selection and Final Development Decisions, it will have little impact on the Introduction Decision criteria where there may be sig-

nificant social-private disparities. Even if our society refuses to price fuels at their social value, and maintains a Clean Air Act which discourages major technological changes, there are other steps which can be taken. Some sort of automotive fuel economy standard, such as those recently discussed in Congress, would certainly have an impact on the Introduction Decision, serving as a very crude proxy for the social premium on fuel. The impact would, however, depend on just how the legislation were written and implemented. Vehicle standards, tied to the "available technology", would be less effective than a more flexible approach utilizing gradually tightening fleet standards, allowing for the phase-in of new systems. As with the Clean Air Act, such a mechanism could cause significant disruption of automotive sales if the attributes of the system being gradually displaced were perceived by consumers as superior to those of the Stirling. Such measures would obviously apply to the minor evolutionary changes, toward which the industry is naturally inclined, as well as major innovations such as the Stirling engine.

The government may want to intervene in the automotive market with the express purpose of commercializing Stirling technology. Given the large and risky nature of a positive Stirling Introduction Decision, a logical government role would be to reduce either the magnitude of the funds risked or the probability of failure. The former could be accomplished by a direct subsidy of the Introduction Stage. Of less impact, but less expensive for the government, would be some sort of guaranteed (limited industry liability) loan or other risk-bearing function by the government. To the extent that such measures are considered appropriate for the commercialization of other energy-related technologies (such as the supply of synthetic fuels), they would be appropriate for consideration in the commercialization of a petroleum-conser-

ving technology such as a Stirling-powered automobile.

Such measures would reduce the firm's possible dollar loss involved in a Stirling introduction, and would be appropriate if it is the reticence of the industry to make a major technological change that is considered the relevant market failure which government is attempting to correct. If, however, it is a social premium on fuel that is the relevant problem, such measures would have limited impact, as they would not directly affect the automobile buyer's decisions and thus have little impact on the ultimate success of commercialization. As discussed above, a positive social premium on fuel causes an undervaluation of any fuel-conserving technology, which we are here (of course) assuming the Stirling engine to be. The most straightforward measure, then, is to align the private and social values of fuel. A less direct approach to the general problem, but with a similar impact on the automotive TD&P process, would be a direct subsidy to purchasers of Stirling-powered vehicles. In this case, however, there is no reason why such a measure should not apply to other low-fuel-consumption vehicles. A tax/rebate system for high/low fuel consumption vehicles would of course have similar effects. Such a system might well be utilized in combination with a risk-reduction measure such as those discussed above.

5.4.4 The Ford Proposal

In the previous subsection we emphasized that if R & D on the FGS Stirling system is to be supported by the government, the best type of arrangement would be a cost-sharing program with one of the Big Three. At this time, this effectively means financing part of the Ford program. GM continues to maintain its position that the Federal Government should not support

(and GM would not accept) R & D which is more closely related to an automobile than Basic or Applied Research, and that the Stirling is extremely unlikely to ever be cost-effective. Chrysler agrees with GM on the second issue, and has long maintained that the gas turbine is the engine of the future. The policies of GM and Chrysler may be in the process of changing, especially if government funds become more widely available. We will deal here, however, with Ford's public proposals.

As discussed in Section 5.2, Ford is actively engaged in development of a Stirling-powered vehicle. They have laid out an optimistic schedule for Final Development and an Introduction Stage, with model year 1985 as the introduction target date. They estimate a total cost from the present through completion of Final Development (in 1981) of \$100-200 million, and have stated that they will not allocate this amount of money internally. They are in the process of preparing proposals to the Energy Research and Development Administration for substantial support of their Final Development program. Ford obviously has the proven competence for the manufacture and design of automotive systems that will sell, and the incentives to get the Stirling system to the marketplace. Their willingness to foot a substantial fraction of the bill gives them a clear stake in a positive outcome. This is the type of program the government should be looking for on the Stirling engine, and the type of behavior by the Big Three that should be encouraged by the government. It is an opportunity for our society that should not be passed up.

There is, however, an inherent difficulty in this type of cost-sharing program, namely finding an equitable division of support between the government and the company involved. To pose the question quite baldly: If Ford is so interested in the Stirling, why don't they fund the program entirely

on their own? Is their proposal merely a plan to get the taxpayers to fund a program they would fund themselves anyway? If the government accepts their proposal, then obviously there will be no way to know the answer to these questions. However, in Chapter 3 we discussed the various reasons why the automotive industry's own self-interest will very likely lead it to underinvest in major technological innovations; we will not review that material here. It is very plausible that Ford would not adequately (from a social standpoint) fund a major new technology program which they view as extremely risky. If the government chooses not to fund Stirling engine development at all (beyond the present \$550,000 contract with Ford), the most probable result will be (as Ford has said) that the Ford program will continue at a relatively low level of funding, possibly attaining success at some date well after 1985.

If the government invests in the Ford program and either Ford would have funded it anyway or the program simply fails to produce a viable engine, the worst that can happen is that the government has lost up to about \$100 million.¹ On the other hand, as discussed in Section 5.3, society may well gain benefits in the \$billions. The probability of commercial success (given the marketplace conditions and government interventions extant) would be higher under this type of arrangement than any other, due to Ford's stake in a positive outcome. If the Ford program proved unsuccessful, it at least would have accelerated a determination that the FGS Stirling is not a viable alternative to the advanced ICE (or inferior to another alternative) and allow both Ford's and the government's resources to be diverted either to advanced

¹Of course the money would not really have been "lost" -- information on Stirling technology would have been obtained.

Stirling concepts or to other systems.

An alternative or supplement to funding Ford directly would be to fund automotive component suppliers or other firms for the development of specific components to be supplied to Ford. This is the procedure used by the ERDA program in its gas turbine development effort, which is centered at Chrysler. There are other alternatives which we have not analyzed. At this stage in the development of the FGS System, however, it is clear that the automotive industry (i.e., not a government laboratory or a research-oriented firm without a relevant product line) should be the center of the R & D activity.

5.5 The Stirling Engine: Summary and Conclusions

In this chapter we have attempted to analyze the benefits from government support of Stirling engine development efforts and how those benefits might best be obtained.

First, we examined the status of Stirling engine technology and the extent and focus of present Stirling engine R & D efforts. The Stirling engine is neither an infant nor a mature technology -- it has been the subject of development efforts for several decades but has never been produced in significant quantities. At the present time the Stirling technology can be divided into two subsets: 1) a "First Generation System", consisting of components each of which has been in dynamometer testing for several years, and which has demonstrated a high likelihood of meeting all the necessary requisites for a successful passenger car powerplant except initial cost, and 2) "Advanced Systems", involving concepts with potential performance and/or cost advantages over the FGS but which have not yet been shown to be technologically

viable. The most important distinction is that the FGS uses no load-bearing components made from ceramic materials. The key non-cost attributes of an FGS Stirling-powered automobile are unlikely to change significantly as development efforts proceed; the focus of the efforts will be to minimize its cost, through engine optimization and component choice and design. An FGS-powered vehicle might, if the development process proceeds well and is adequately funded, be marketed in the mid-1980's.

The economics of the Stirling system were next examined, from a strictly social viewpoint. The analysis was concerned principally with the FGS Stirling; of the various Advanced Systems, structural ceramics stand out as clearly deserving of R & D support, and the relatively basic nature of the work precludes the utility of economic analysis. First a number of general issues in the evaluation of alternative automotive powerplants were discussed and a very simple total operating cost model for the FGS Stirling system developed. Then a very crude cost-benefit analysis was performed. The benefits of Stirling engine commercialization, relative to continued use of the ICE, are extremely uncertain. The principal technological uncertainty is its initial cost, but its social value at any initial cost depends on the price of fuel, the type of fuel used, and the technological features of the contemporary ICE. The present value of the future benefits of displacement of the ICE by the Stirling was shown to be very much larger than the likely government investment in R & D, and we therefore concluded that such an investment is a very good gamble for the government to take.

How, then, should the government proceed to determine whether the Stirling can in fact be made socially beneficial, and, if it can, what roadblocks might there be to block its commercialization? This was next addressed.

First, the process by which the Stirling system would be introduced into the marketplace was examined; transitional roadblocks are apparently minimal except that the fuel-insensitivity of the engine would not likely be utilized to advantage at first. Then the disparities between social and private calculations of the vehicle's economics were examined. The disparities may be significant; and thus the decision criteria in the TD&P process are likely to be more stringent than socially desirable. Unless our society decides to price fuel at its social value, or take other measures to encourage the adoption of fuel-conserving technology, government support of R & D is shown to be an inherently limited policy tool. Some desirable features of a government-supported R & D program were then discussed. Finally the proposal by the Ford Motor Company for a cost-sharing Stirling development program was discussed. Ford has the proven competence and the incentives structure to bring the Stirling system to the marketplace, and there are good reasons to believe that Ford will not find it in its own self-interest to invest in the system at the socially desirable level. We therefore conclude that the Ford proposal is an opportunity that should not be passed up.

Several further issues deserve to be addressed to place this discussion of the Stirling engine in a broader perspective. First, as discussed in Chapter 3 of this report, the alternative automotive powerplant R & D program must be viewed as a portfolio of programs, some of which will likely fail, i.e. not reach commercialization, if for no other reason than the fact that, while they achieved their technical goals, other systems turned out to be superior. There is a tendency, especially in politically visible programs such as this, to view individual programs in isolation and consider funds expended on systems not ultimately commercialized as having been a waste of government

resources. Such a tendency must be resisted; in selecting a portfolio of R & D programs it must be expected that they will not all succeed.

Second, we have neglected discussion of markets where the Stirling engine might be successfully commercialized as a stepping stone to the passenger car application. In particular, the heavy duty prime mover market should be carefully analyzed and the Federal program accommodated to it if appropriate.

Finally, it is hard to avoid comment on some of the features of recently proposed legislation related to Federal alternative powerplant R & D programs. First, it must be recognized that the transition to a major new automotive powerplant would of necessity be a long, tedious and carefully orchestrated program, as we hope has been made clear in the preceding discussion. There is little point in mandating the crash development of demonstration systems when no significant impact on the national goals of reduced automotive fuel consumption and ambient air quality could result from a Stirling engine commercialization until around the turn-of-the-century. Second, given the magnitude of the present automotive manufacturing, servicing and fuel supply system, it is of the utmost importance that care be taken to integrate the R & D program with it. In particular this means that we must recognize that the present institutional structure must be incorporated into the Federal R & D process. This has been emphasized in the discussion of the Stirling system, but is generally missing in the legislation which has recently been proposed.

6. THE DIESEL ENGINE

6.1 Introduction

A number of the alternative engines -- the stratified charge engines, the Wankel and the diesel -- are close in concept, design and stage of development to the conventional spark-ignition engine. All these engines are "internal combustion engines" (though we have followed popular usage and used this term to denote the conventional automobile engine only). They are all quite well developed engine technologies -- versions of these engines are already in mass production in either Europe or Japan, or in the Final Development Stage in the U.S. Most of the industry's standard design practices, and much of its ICE experience, would be directly applicable to these alternatives. These engines are (or would be) manufactured and assembled on engine production lines very similar to those used to produce the ICE today, and indeed do (or would) use a great many common machine tools and existing engine components.

These engines thus present a different set of issues to the government R & D planner than do the advanced heat engines (of which class we analyzed the Stirling engine) because mass production experience is already available. We have chosen one example of the engines which are "close to the ICE" -- the diesel -- for more detailed examination in this chapter. The diesel is especially interesting because it is already in mass production and use in automobiles (though on a modest scale relative to total U.S. auto production), and it does offer significantly improved vehicle fuel economy. Many in government and elsewhere are enthusiastically promoting the advantages of much greater use of diesel engines in automobiles in the U.S. Yet there are special problems associated with its emissions and performance characteristics, and the U.S. automobile industry has in the past

shown little interest in its development for introduction in passenger cars. An apparent impasse exists. The issue, then, of whether the government should embark on a substantial diesel engine R & D program, is an important one in the current context where automobile energy conservation is a major national concern.

In this chapter we address this issue in three stages, generally following the logical structure developed in Chapter 3. First we describe the status of the diesel engine technology which is available for mass production within roughly a five year time scale. A description is given of production and R & D programs now underway. The attributes of a "mature" diesel engine technology -- one available within this time frame -- are evaluated relative to the ICE. Second, we examine the social benefits which might be realized from replacement of the ICE by the diesel, and we discuss the constraints which the industry's introduction process is likely to place on the attributes of a diesel engine at the time mass production commences. The major uncertainties or barriers which inhibit the automobile industry from resolving either final development or introduction decisions are thereby identified. Finally, the degree to which these uncertainties or barriers could be overcome by government R & D programs is examined.

Our primary conclusion is that these uncertainties and barriers are not in the attributes of the diesel engine technology itself. That technology is well developed, and the characteristics of a diesel passenger car of given acceleration capability could be (and are being) determined with relatively modest effort by the automobile industry. The diesel engine appears to be an attractive alternative to the ICE at a lower vehicle performance level than its ICE-equivalent vehicle. Gains in fuel economy, lower

fuel price and lower maintenance costs (at this lower vehicle performance level) are likely to more than offset the higher initial vehicle cost. The major uncertainties are threefold. The ability of the diesel to meet future NO_x emission standards is in doubt and there is concern that currently unregulated diesel emissions may be subject to strict control if large-scale use appears likely. The size of the market for diesel cars with much reduced performance relative to equivalent ICE vehicles is unclear. And uncertainties in the ICE baseline continue to introduce uncertainties into calculations of benefits of diesel engine use of the same order as the benefits projected from such use. We will now develop these arguments in detail.

6.2 Status of the Technology and Current R & D Programs

6.2.1 A Review of Diesel Engine Technology

The diesel engine is no newcomer as an automotive powerplant. In those parts of the world where fuel costs are higher, personal incomes are lower, and fuel economy and engine durability have been much more important than in the U.S., the diesel engine has penetrated into the light duty vehicle market. Lightweight, high speed diesel engines have been developed specifically for these conditions in Europe and Japan where automotive fuels are much more expensive than in the U.S. The more economical diesel is used in taxis, delivery vans, and other high mileage urban vehicles. While diesel engine passenger cars are not currently produced in the U.S., Daimler-Benz and now Peugeot market diesel and ICE-powered versions of their same basic vehicles in this country. The number of diesel vehicles sold here is, however, small (a few thousand per year). In the larger engine size ranges the diesel is produced by several manufacturers in the United States. The diesel engine is generally used in the heavy truck and commercial bus market.

It is also used extensively in many other areas for power generation or propulsion.

The diesel engine is an "internal combustion engine" superficially quite similar to the conventional automotive spark-ignition engine. The fundamental difference between the two engine types is in the method used to ignite the fuel-air mixture inside the engine cylinder. From this fundamental difference follow differences in the characteristics of the fuels, methods used to prepare the fuel-air mixture, the details of engine design, and engine operating characteristics. In the conventional gasoline-fueled spark-ignition engine the fuel-air mixture is ignited by an electrical discharge at the spark plug towards the end of the compression stroke, and a turbulent flame propagates across the cylinder at a rate determined by cylinder head and piston geometry and properties of the fuel-air mixture. This mixture is prepared in the engine intake system with a carburetor (or in some cases fuel injection in the intake port). In the diesel engine, the fuel-air mixture ignites spontaneously close to the end of the compression process, as the temperature and pressure of the mixture in the cylinder increase and chemical reaction rates become sufficiently fast to initiate combustion. Control of this process is achieved by requiring certain fuel characteristics¹, and by producing within the engine cylinder a mixture which is ready to burn at the appropriate time. Fuel injection directly into the engine cylinder just before combustion commences, and suitable design of injector, cylinder head and piston geometries, achieve the desired rate of fuel-air mixing.

¹A cetane number is used to characterize the ignition quality of diesel fuel. A certain minimum cetane number is required for acceptable engine operation.

This difference in method of ignition and of controlling the rate of burning of fuel-air mixture leads to perhaps the most important design and operating differences between these two engines. The diesel can operate at a higher engine compression ratio than the spark-ignition engine because detonation (or knock) is not a limiting factor. Also, power levels lower than the maximum engine output are obtained in the diesel by reducing the fuel flow while the air flow remains unthrottled. In contrast, in the spark-ignition engine, both fuel and air are throttled together. The higher compression ratio, and unthrottled air flow at part load, combine to give the diesel engine its higher operating efficiency.

But with these advantages come the reasons for the higher initial cost and heavier engine weight of the diesel. Higher compression ratios and rates of pressure rise in the cylinder during combustion in the diesel generally require heavier and more rugged engine components -- engine block, cylinder head, crankshaft, bearings, etc. The diesel fuel injection system is significantly more expensive than the carburetor on the gasoline spark ignition engine. Difficulties in starting the diesel when the engine is cold require a heavier duty battery and starter. Furthermore, for a given engine displacement, the maximum power obtainable from a diesel is less than from a spark-ignition engine because objectionable exhaust smoke levels limit the mass of fuel which can be burned in the diesel per unit mass of air to below normal spark-ignition engine values. Thus, specific power (maximum power divided by engine weight) for the diesel is lower, and initial engine cost for the diesel is higher. This trade-off for the diesel -- higher efficiency achieved at the expense of lower specific power and higher initial cost -- is an important issue which will recur throughout this chapter.

The emissions characteristics of the two engines are also different (again due to the different combustion processes). The diesel's hydrocarbon and CO emissions are lower than engine exhaust emissions from a typical spark-ignition engine. NO_x emissions are about the same, but the diesel cannot use a catalyst to achieve further NO_x reductions in the exhaust system. Particulate and sulfur oxide emissions from the diesel are substantially higher, but in automobiles these pollutants are not yet subject to regulation. The degree of NO_x emission control which the diesel-engine passenger car can achieve, and the impact of diesel particulate emissions if diesels significantly penetrate the market are important issues we will consider further.

There are several distinct types of diesel engines. A major reason for this is the effect of changes in cylinder size on the diesel combustion process. As the size of the engine cylinder is decreased, the intake port, cylinder head and piston geometries must be modified to maintain the appropriate rate of mixing fuel and air necessary for good combustion and thus engine performance. As a consequence, engine configurations change as engine size (and application) change. Direct injection (DI) engines, where the fuel is injected directly into the combustion chamber between the piston and cylinder head, are used at the larger size and lower speed end of the spectrum, where slower fuel-air mixing rates are acceptable. Indirect injection (IDI), engines where the fuel is injected into a separate combustion chamber which is connected to the main combustion chamber through a nozzle, are used at the smaller size and higher speed end of the spectrum where faster fuel-air mixing rates must be achieved. IDI engines are often called prechamber or swirl chamber engines depending on the details of the separate combustion chamber geometries. Also, for each type of engine, each diesel engine manufacturing company has developed its own design practices,

and a variety of engine geometries across the different engine manufacturers results. There appears to be no unique optimum configuration for any given application.

One potentially viable engine option for passenger car diesels, which addresses the problem of low specific power, is turbocharging. The power output of a diesel or spark-ignition engine of given displacement is limited by the maximum air flow through the engine. Given this maximum airflow, the fuel flow is then fixed for the diesel by the fuel-air ratio at which smoke becomes objectionable and for the gasoline engine by the available oxygen in the air. A compressor can be used to increase the air density at the engine intake; the airflow and consequently the fuel flow and engine power, for a given displacement engine, are thereby increased. The compressor can be driven by a turbine fitted to the engine exhaust. Thus engine weight for a given vehicle performance may be reduced. However, engine cost increases, and there is currently no consensus as to whether naturally aspirated (nonturbocharged) or turbocharged diesel engines are the more promising for passenger car applications.

In summary, the diesel engine choices for any given application are: diesel engine type (DI or IDI), and turbocharged or naturally aspirated. In addition, for each diesel engine type, manufacturers offer a range of engines which differ substantially in the details of the design. Presently available automotive (car and truck) diesel engines can be grouped roughly by diesel engine type, according to engine size, as follows:

- 1) Passenger car engines: naturally aspirated small high speed engines with swirl chamber or prechamber configurations, with maximum power in the 40 to 80 hp range at 3000 to 4000 rpm.

- 2) Intermediate size engines: generally naturally-aspirated and direct-injection medium-speed engines, with maximum power in the 120 to 200 hp range at 2500 to 3000 rpm.
- 3) Large size engines: usually turbocharged direct-injection low-speed engines, with maximum power above about 300 hp at 2800 rpm.

None of these engines are suitable to power U.S. passenger cars in the intermediate and full size ranges -- the categories where the greatest potential for national fuel conservation exists; see Table 6.1 which follows. Across the entire spectrum of car sizes, diesel engines for U.S.-manufactured passenger cars would be in the 80 to 200-plus hp range, depending on car size (subcompact to large) and desired maximum acceleration characteristics. [8] These would be indirect injection high speed engines, and perhaps would be turbocharged. Suitable engines of this size range are not currently available in the U.S. As a consequence, there is considerable confusion as to the likely performance and fuel economy characteristics of diesel engine vehicles which might be developed for production. Also, there is some disagreement as to whether existing types of diesel engines are the optimum for this new application.

6.2.2 Current Automotive Diesel Usage

U.S. fuel consumption by autos, trucks and buses, divided by vehicle classes, puts current diesel engine usage and the potential for expansion of diesel use in context. Table 6.1 shows the number of vehicles registered in the U.S. in December 1973, broken down into vehicle weight categories. Fuel

Table 6.1

FUEL USAGE BY VEHICLE TYPE [81]

Vehicle Type	Vehicles registered Dec. 31, '73 in millions	Distance travelled in CY 1973 billions of miles	Percent total highway fuels used in each class ¹	Diesel as percent of fuel usage in each class ²
Passenger cars				
subcompact	28.5	203	8.3	0
compact	17.3	152	7.0	1
intermediate	18.3	203	16.3	0
full size	37.7	458	38.8	0
total	101	1016	70.4	
Trucks				
I < 6000 lb.				
II 6000-10,000	12.6		8.9	0
III 10,000-14,000	4.8		3.6	0
IV 14,000-16,000	0.25		0.19	0
V 16,000-19,500	1.3		1.5	0
VI 19,500-26,000	2.4		3.1	4
VII 26,000-33,000	0.48		1.2	45
VIII < 33,000	1.1		9.9	79
total	23	267	28.6	30
Buses				
School	0.33	2.4	0.30	0
Commercial	0.09	2.5	0.47	75
total	125	1288	100	8.9

¹On a volumetric basis. Note a gallon of gasoline is equivalent to 0.88 gallon diesel on an energy content basis.

²Total fuel usage in millions of gallons (CY 1973); gasoline 100,636; diesel 9,837.

consumed -- gasoline and diesel -- is also shown. Passenger car fuel usage (gasoline) is 70 percent of the total; truck fuel usage is 29 percent. Diesel fuel is significant only in the heavy truck classes, and is 9 percent of the total fuel consumed. The diesel has penetrated the automotive market in applications where two key requirements are met. The first is that vehicle operators are responsive to total life-cycle vehicle cost calculations. The second is high mileage usage which places a premium on durability, and low maintenance and fuel costs. As a result of increased petroleum prices, diesel engines are expected to increase their share of the market at the heavy truck end, and in light truck, van and taxicab categories. One European manufacturer expects to double diesel engine production by 1980.

Another characteristic of the current diesel engine market important to our discussion is its size and diversity. U.S. production of diesel trucks is about 150,000 per year. [82] This includes many engine sizes from several engine manufacturers. Thus, production volume for a given size and manufacturer is one or more orders of magnitude smaller than is typical of passenger car gasoline engines. The U.S. diesel engine industry has, in the past, shown little interest in passenger car diesel engine applications. The U.S. automobile industry has shown a similar lack of interest in this application,¹ though two of the Big Three have considerable diesel engine experience. One of the European diesel vehicle manufacturers, Opel, is a GM subsidiary. GM (through Opel and through Detroit Diesel), and Ford (in their European division) have extensive experience with the diesel technology, ranking first and second respectively, in world-wide diesel engine production.

¹Current automobile industry activities are discussed in the next section of this chapter.

While diesel engines of a size suitable for U.S. passenger cars are not manufactured in this country, diesel light-duty vehicles are manufactured in Europe and Japan. Daimler-Benz (which produces the Mercedes-Benz), and recently Peugeot, market diesel and gasoline ICE versions of the same basic vehicles in the United States. The numbers sold here are small (a few thousand per year). Nonetheless, these vehicles have been extensively tested, and the performance and emissions characteristics widely quoted, in attempts to evaluate the attractiveness of the diesel as a passenger car engine. Passenger car diesel engine development in Europe has a history going back several decades, and a long sequence of product improvements have been made. As evidence of this continuing evolution of improved light-duty engines, both Peugeot [83] and Daimler-Benz [84] recently introduced new diesel engines in their passenger cars, with the primary aim of improving vehicle acceleration.

Because of renewed interest over the past few years in the diesel for passenger car applications, the operating characteristics of vehicles currently available with diesel engines have been carefully measured and documented. The Mercedes, Peugeot, Vauxhall, Opel and Nissan diesel cars (naturally aspirated indirect injection engines with either a swirl chamber or prechamber) have been evaluated, and in many cases vehicle attributes compared with those of the same vehicle with its conventional gasoline ICE option. We have chosen to summarize the results of these studies in Table 6.2 by listing, for the best diesel technology now available, the ratios of diesel engine and gasoline engine attribute values, to make two points.

Table 6.2

PERFORMANCE CHARACTERISTICS OF CURRENT DIESEL ENGINE
CARS RELATIVE TO GASOLINE ENGINE VERSION OF
SAME VEHICLE¹

Vehicle weight; diesel/gasoline	1.0 - 1.07
Engine displacement; diesel/gasoline	1.04 - 1.3
Engine max. power; diesel/gasoline	0.56 - 0.9
Vehicle max. speed; diesel/gasoline	~ 0.8
0 - 60 mph acceleration time; diesel/gasoline	1.4 - 1.6
Vehicle fuel economy; ² diesel/gasoline	1.19 - 1.34
Noise; diesel noise above gasoline	
drive-by	2 dBA
idle	8 dBA
Emissions	
HC diesel/HC gasoline	≈ 0.1 - 1 ³
CO diesel/CO gasoline	≈ 0.1 - 1 ³
NO _x diesel/NO _x gasoline	0.5 - 1

¹ These ratios are obtained from references [85]-[87] where Mercedes 240D and 300D, and Peugeot 504D were compared with their gasoline ICE equivalent vehicles.

² Fuel economy expressed on a miles per gasoline-equivalent gallon basis (i.e. per unit fuel energy). Average of urban and highway EPA cycles.

³ Low value for diesel compared with non-catalyst gasoline vehicle. High value compares diesel with gasoline vehicle with oxidation catalyst and optimum emission controls

The first point is that the gasoline and diesel versions are essentially the same basic vehicle with different engines fitted under the hood. The reason for this is to hold the costs of integrating the diesel into the vehicle body to a minimum. Current diesel vehicle production volumes are not large enough to justify major vehicle body changes. Depending on the particular comparison made, these diesel engines have displacements closely equal to the equivalent gasoline engine displacements, and engine weights of order 100 lb. heavier. The displacements are about the same so that the two engines share as many common parts as possible.¹ The diesel vehicle weight penalty, at about the same engine displacement, is primarily in the engine, starter and battery. At roughly equal engine displacements, the increase in diesel engine weight can be accommodated in the existing vehicle body with only minor body changes.

The second point follows from this. The maximum power of the diesel engine option is considerably below that of the gasoline ICE option, because present diesel engine technology has a significantly lower power-to-displaced volume ratio (and power-to-weight ratio) than gasoline ICE technology. Thus, given the requirement that engine displacements must be roughly the same, the diesel engine version must inherently have significantly poorer vehicle performance characteristics than the gasoline

¹The Mercedes 300D is the exception to this generalization. However, it represents a further level of engineering development (undertaken to improve diesel vehicle performance) beyond the equal displacement stage described above.

ICE version. If vehicle performance were to be the same, then a considerably larger diesel displacement would be required, and because of the resulting engine weight increase, much more substantial vehicle body modifications would be necessary for the diesel version. This places important constraints on the diesel engine introduction process which we discuss further in Section 6.3.

The data in Table 6.2 supports this analysis. The table shows maximum engine power, and maximum vehicle speed significantly lower for the diesel engine versions; 0-60 mph acceleration times are correspondingly much longer. Furthermore, presumably these diesel engine vehicles are designed for that part of the market which is especially concerned with vehicle lifetime fuel costs. By using the same vehicle body as the gasoline engine version (which is manufactured in larger numbers) and by using a more efficient basic engine at a lower power to vehicle weight ratio and allowing a cheaper fuel to be used, the diesel engine version has (in a rough sense) minimized the initial vehicle cost increase and maximized the fuel cost savings. The degradation in vehicle performance that results is apparently a price that purchasers of these vehicles are willing to pay.

The emissions comparisons in Table 6.2 are not especially useful for projecting future trends because the gasoline engine vehicles were not equipped with catalytic converters nor with advanced emissions controls. Nonetheless, the engine emissions of the diesel are roughly an order of magnitude lower than emissions leaving the gasoline engine exhaust port (i.e., prior to the catalytic converter for HC and CO), and

between a factor of one to two lower for NO_x . The emission control potential of the two engines is not the same, however, as a result of their different combustion characteristics. The emissions status of the diesel as an alternative engine is discussed in Section 6.2.4.

6.2.3 Status of R & D Programs

Diesel engine R & D is being carried out by the diesel engine manufacturers, the automobile industry and various R & D organizations. The interests of these three groups are quite different. The diesel engine manufacturers have had to carry out the R & D necessary for their engines to be able to meet (or be prepared to meet in the future) the applicable emissions and noise standards for their product line (which are primarily heavy duty engines). They also, of course, pursue activities in the product improvement stage of development as they seek an improved competitive position and expanding markets for their products.

The R & D activities of Ford and Chrysler on the diesel as a passenger car engine have been exploratory in nature. The characteristics of currently available diesel engines have been evaluated, existing diesel engine vehicles have been tested, available diesel engines have been installed in vehicles for evaluation, the emissions reduction potential of the engine has been examined. These programs have apparently not proceeded beyond these exploratory investigations because of the diesel's current inability to meet the 0.4 g/mile NO_x standard, because of concern over possible future standards for currently unregulated emissions

such as particulates, and because of uncertainties as to the market for diesel automobiles which would have several different characteristics from current U.S. gasoline engine vehicles.

In contrast, General Motors, in its Oldsmobile Division, has embarked on a passenger car diesel engine development program. The diesel engine design is based on the V-8 350 CID gasoline engine with the goal of using the same engine block and as many other components as possible. The design is a prechamber engine with a 20:1 compression ratio. Apparently, some firm tooling orders for the diesel have been released and a supplier for the fuel injection equipment has been identified. Sources predict that the Oldsmobile diesel could reach production in mid-1977 or 1978. [88] Reports also say that the diesel will be supplied to Chevrolet and GMC for use in light pickup trucks. However, GM officials have repeatedly stated that the corporation would not put the diesel into production until the government relaxed future NO_x emission standards. It is believed that Chevrolet is also developing a smaller diesel than Oldsmobile's, for one of its car lines.

Volkswagen has an active diesel engine development program. It is apparently very close to a production decision. A version of the engine has been demonstrated in VW Rabbit vehicles in the U.S. to EPA, DOT and ERDA. VW has utilized its standard 1,475 cc engine with a diesel upper end. The design is an indirect injection engine with a 23.5:1 compression ratio giving 48 brake hp at 5000 rpm. The impact of the lower diesel engine power has been reduced by use of a 4.22 ratio final drive.

Apparently the high low-speed torque characteristics of the diesel give good performance at low vehicle speeds in high gear. [88] VW also believes the diesel has a promising future in the light-duty truck area. In discussions with VW engineers, we were given the impression that the major question is "how many" diesel engines they will provide, and not "whether" diesel introduction will occur. [89]

A recurring theme in industry statements concerning these automotive diesel R & D efforts are the inhibiting effects of the 0.4 g/mile NO_x standard, and potential particulate emissions problems for the diesel.

The U.S. government has funded a number of programs to evaluate automobile diesels. One of these efforts is a development program; ERDA has initiated a diesel engine program, currently at the \$1 million/year level, with the ultimate goal of demonstrating an advanced six cylinder turbocharged 130 hp diesel engine concept in an automobile, which meets the 0.4 g/mile NO_x standard. The technology advances which will be sought include lighter engine weight, variable compression ratio engine design, cheaper fuel injection system and significantly lower NO_x emissions than has been achieved to date. The first stage of the program consists of extensive testing on an Opel engine, a single cylinder engine test program, and a preliminary design study. This program has the intention of developing diesel engine technology substantially beyond today's levels, and then demonstrating this potential in a passenger car.

Outside of these development activities, a number of information gathering and assessment studies have been completed, mainly supported by government funds. There has been a high level of interest in, and even advocacy for, the diesel within government circles, because of the good fuel economy currently available diesel vehicles exhibit and the inherently low CO and hydrocarbon emissions.

EPA has funded a number of studies to quantify the emissions characteristics of present diesel engine passenger cars, as well as an overall light-duty diesel technology assessment. DOT has sponsored several studies in which the fuel conservation aspects of the diesel in passenger cars have been evaluated. We will review some of the results of these studies in the next section.

6.2.4 Attributes of the Automotive Diesel

In this section we will review the attributes of current automobile diesel engine technology, and assess the potential for substantial improvements in these attribute values. At the outset it is worth emphasizing the different status of the diesel and the Stirling engine technologies. In Chapter 5, the Stirling engine, at the first generation level, was characterized as at the end of the Initial Development Stage. In contrast, the diesel engine is a highly developed technology, well into the Mature Production Stage, for a large number of applications including automobiles. There is extensive experience in Europe and Japan with the manufacture, sale, and operation of light duty diesel engines in passenger cars, taxis and light trucks. There is a long history of

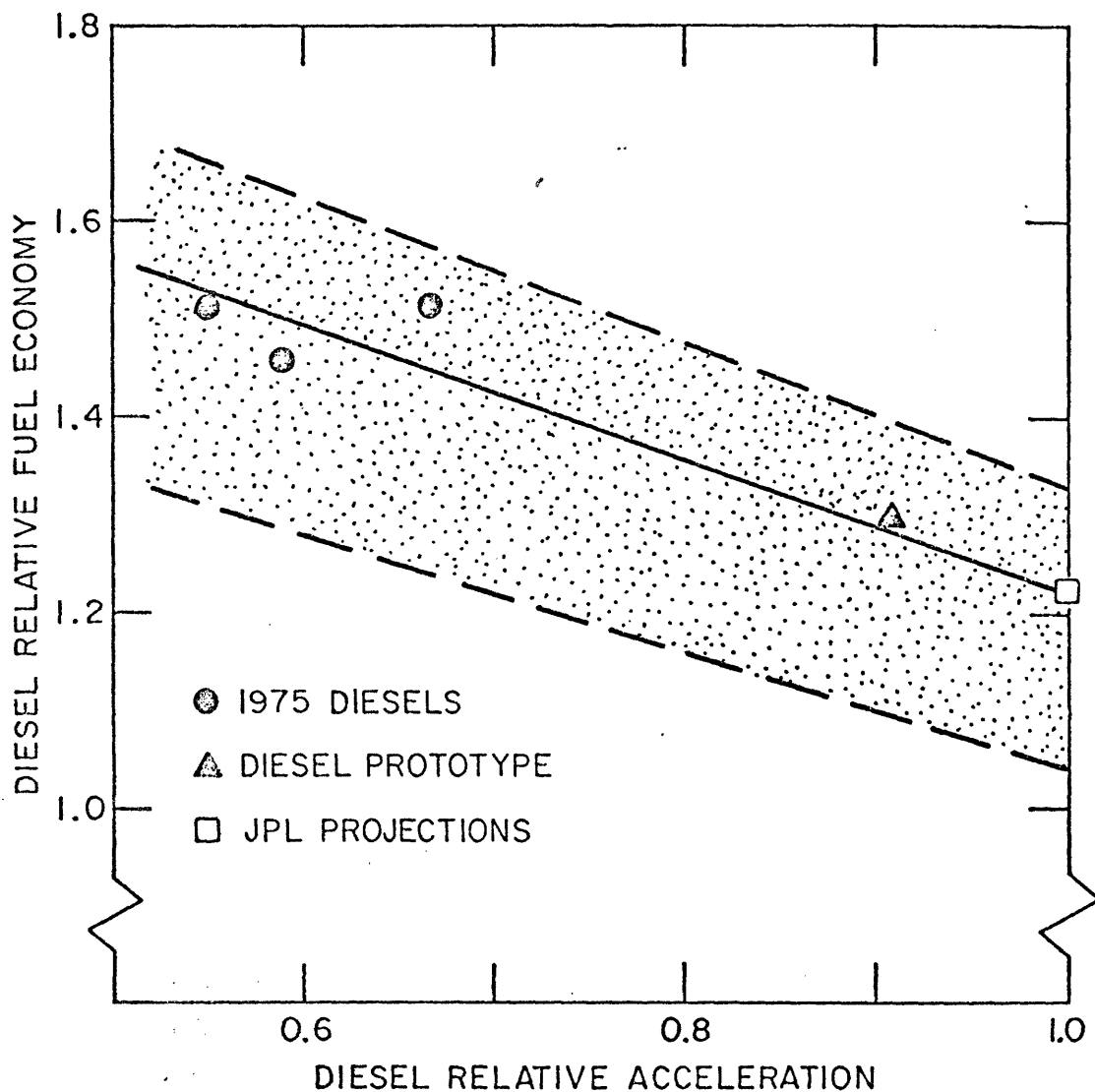


Figure 6.1

DIESEL VEHICLE FUEL ECONOMY RELATIVE TO AVERAGE EQUAL SIZE ICE VEHICLE (ON MILES PER GASOLINE EQUIVALENT GALLON BASIS) AS A FUNCTION OF RELATIVE MAXIMUM VEHICLE ACCELERATION (0 TO 60 MPH TIME). SOLID LINE RELATIVE TO AVERAGE 1975 ICE; BAND RELATIVE TO 1980 ICE.

steady product improvements to increase the specific power of the diesel relative to the ICE, improve the fuel economy of the engine and reduce its initial cost. The diesel engine technology, for automobiles, is already at a mature stage in its development.

What creates a problem in evaluating the diesel engine for the U.S. auto market is not that diesel engine experience is unavailable, but that vehicle performance data are not available for engine-vehicle combinations roughly equivalent to U.S. intermediate and full-size cars. Thus, one is led to the conclusion that if a major U.S. auto manufacturer makes the decisions to first develop and then introduce an automotive diesel for the U.S. market, the engine technology is likely to be primarily a scaled-up version of the light-duty engine technology now available in Europe, incorporating perhaps some modest improvements resulting from the greater R & D resources the Big Three have in comparison to existing diesel engine manufacturers. We will now review the attributes of that technology, relative to the ICE, and return to the question of more "advanced" diesel engine technology at the end of this section.

A number of recent studies have reviewed the characteristics of a light-duty diesel engine as it might be used in a passenger car in the near-term future (say prior to 1980). [7,8,42,53]. These assessments all see the indirect injection engine, with either a prechamber or a swirl chamber, as the best engine type for this application. Table 6.3, based mainly on the Ricardo study [42] summarizes the attributes expected of a first generation diesel passenger car built for

Table 6.3

ATTRIBUTES OF AVAILABLE-TECHNOLOGY DIESEL

<u>Attribute</u>	<u>Importance</u>	<u>Status</u>
Initial Cost	Critical for consumer acceptance.	Somewhere between 1.5 and 2 times cost of equivalent-hp gasoline ICE.
Emissions	Legal requirements for HC/CO/NO _x , though future levels unclear.	Meets strictest standards proposed for HC/CO. NO _x limit 1-2 g/mile depending on vehicle and engine size. Possible future problems with particulate, odor and perhaps other currently unregulated emissions.
Efficiency	Key consumer and legal requirement, and of social value.	Most efficient currently available powerplant for light-duty use. However, either vehicle fuel economy or acceleration must be compromised due to low specific power.
Weight	Key factor in cost, vehicle design and vehicle performance.	Greater weight would require body modifications.
Packagability (shape and volume)	Key in determining whether major vehicle modifications needed.	Greater in volume and height than equivalent power gasoline engine. Turbocharging reduces volume but increases complexity.
Torque-speed curve shape	Determines engine max. power for given vehicle performance, and transmission requirements.	Diesel and gasoline ICE have similar torque characteristics. If diesel runs at lower speeds, heavier transmission may be required.

Table 6.3 (Cont'd)

Noise	Consumer and socially appreciated attribute, will become legal requirement.	Drive-by noise levels for diesel vehicle higher than gasoline ICE vehicle. Idle noise major problem area requiring attention in vehicle design.
Vibration (smoothness)	Consumer requirement; impacts on vehicle design.	Higher than gasoline ICE, especially at idle. Will require special engine mountings.
Power response and driveability	Key consumer requirement.	Satisfactory. Cold engine driveability as good as hot engine driveability and better than gasoline ICE.
Maintenance requirements	Key consumer requirement.	Minor maintenance requirements similar to gasoline ICE. Major overhaul required less frequently. Likely cost savings.
Response to abuse and neglect	Key consumer requirement.	Probably satisfactory.
Starting characteristics	May be important consumer requirement.	Inferior to gasoline ICE; starting aid required. 15-30 second delay.
Safety	Consumer and possibly legal requirement.	Safer than ICE since fuel is less volatile than gasoline.
Design versatility	Key in reducing long run production cost.	Equivalent to gasoline engine.
Fuel versatility	May allow use of less expensive fuels in short term.	Diesel fuel presently cheaper than gasoline; but diesel fuel availability and cost are constrained by cetane number requirement.

the U.S. market, and identifies the critical technological problem areas. The major advantage relative to the ICE is the higher engine efficiency, which offers the promise of significant fuel economy improvements. Secondary advantages are fuel at lower prices (in the short term, at least) and potentially lower maintenance costs. The major disadvantages are the magnitude of the engine's emissions of both regulated and currently unregulated pollutants, the engine weight and size, and noise characteristics, as they impact on vehicle integration, and manufacturing cost. Less critical areas, which nonetheless create uncertainty about marketing the diesel as a passenger car engine on a large-scale, are the vehicle owners' response to cold starting problems, noise, vibration, odor and fuel availability. We will not discuss these problem areas in more detail.

Table 6.4 summarizes the emissions characteristics of current diesel engine automobiles; the comments in the table relate the diesel's emissions to either currently promulgated standards or to typical emission levels of gasoline engine cars using various types of fuel, either with or without oxidation catalytic converters. Satisfactory control of HC and CO emissions is an inherent part of the diesel combustion process, but the inability of the diesel to meet the statutory 0.4 g/mile NO_x standard is generally acknowledged. The NO_x emissions of a diesel passenger car depend on vehicle weight and engine power (as do HC and CO emissions too, though less critically); though estimates of the low

Table 6.4

EMISSIONS CHARACTERISTICS OF CURRENT DIESEL CARS¹

<u>Regulated Pollutants</u>		
<u>Pollutant</u>	<u>Level, g/mile</u>	<u>Comments</u>
HC	0.22 - 3.3 ²	should meet strictest statutory standard (0.41)
CO	1 - 4	should meet strictest statutory standard (3.4)
NO _x	1 - 1.6	depends on vehicle size; approx 1.5 g/mile limit for full size car; will not meet statutory standard (0.4)

Currently Unregulated Pollutants

Particulates	~ 0.3	2 times leaded gasoline engine car emissions; 10 times unleaded car
Aldehydes	~ 0.5	comparable to non-catalyst car; higher than catalyst car
SO ₂	0.3 - 0.6	catalyst car ~ 0.1 g/mile
Sulfates	0.1 - 0.2	comparable to or somewhat greater than catalyst car
NO ₂ :NO _x ratio	0.1 - 0.3	depends on load; much higher than gasoline car
Odor		potential marketing and public acceptance problem

¹Sources [86,87,90]²Higher levels can be easily controlled.

NO_x emissions potential of the diesel are speculative, values in the 1 - 2 g/mile range are often quoted. Additional potential emissions problems for the diesel are particulates¹, sulfate and NO₂ emissions, as well as odor. Particulates are primarily soot, and are of concern due to their submicron size and absorptive surface capacity for other reactive molecules. Sulfur oxides and sulfate emissions are comparable to catalyst-equipped-ICE vehicle emissions because the sulfur content of diesel fuel (≈ 0.5 percent) is an order-of-magnitude higher than in gasoline. The concentration of NO₂ (much more toxic than NO) in the diesel exhaust is much higher than in ICE exhausts. Odor is regarded by many in the diesel engine development business as the hardest emissions problem to sort out and resolve. [89] These currently unregulated pollutants, if emission levels for the diesel are found to be significantly higher than for gasoline engine vehicles, might be subject to regulation in the future; for example, sulfate emission levels are comparable to or greater than emissions from catalyst equipped gasoline ICE vehicles, and future regulation in this area is anticipated before 1980 model year.

It is important to note that exhaust treatment devices such as thermal reactors and oxidation catalysts for HC and CO control, or reduction

¹A particulate emission standard of 0.1 g/mile was suggested by the Dept. of H.E.W. in February 1970, in an Advanced Notice of Proposed Rulemaking, along with suggested standards for HC, CO and NO_x emissions, all for Model Year 1975. [91] It was aimed at controlling particulate emissions (primarily lead) from ICE-powered vehicles using leaded gasoline. All these standards were superseded by the Clean Air Amendments of 1970 and their implementation, which has included standards on lead content in gasoline. No particulate standard was ever promulgated. This 0.1 g/mile suggested standard is sometimes erroneously cited as a possible goal for diesel particulate emissions (e.g., [69, p. 146]) but in fact it is totally irrelevant since it related to both a different health hazard and a different technology.

catalysts for NO_x control, which have been and are being developed for gasoline engines are not useful for diesels. Oxidation in catalysts or manifold reactors is limited in effectiveness by the low exhaust gas temperatures at part load (an inevitable result of the improved efficiency of the diesel). NO_x reduction catalysts are not applicable to the diesel because the exhaust always contains excess oxygen. Particulate, smoke and NO_x controls have been developed by the heavy duty engine manufacturers, as well as the European diesel passenger car manufacturers. The consensus is that the indirect injection light-duty diesel engine has been roughly optimized with respect to current U.S. requirements for HC, NO_x and smoke emissions, and noise, and that significant improvements in one of these areas causes deterioration in one or more of the others.

[89].

Engine weight is another important problem area relative to the ICE. In a comparison made on an equal displacement basis (equal cylinder volume swept out by the pistons), the diesel including necessary auxiliaries is about 15 percent heavier than the gasoline engine. The increase is due in part to heavier engine construction, in part to the heavier engine auxiliaries -- starter motor, generator, battery -- required because these auxiliaries' duty cycle is more arduous, and in part to the fuel injection system. In addition, because exhaust smoke limits the amount of fuel which can be fully utilized with the air inducted into the engine, the diesel's power per unit displacement is less than of the gasoline engine, and for equivalent performance a larger displacement (and thus substantially heavier) engine is required. Development efforts to reduce

the weight of an existing light duty diesel engines to make them more attractive for automobile applications have shown that some weight reductions are realizeable (e.g., [93]). But given the fact that Daimler-Benz and Peugeot recently introduced new diesel engines in their cars in large part to improve the vehicles' acceleration capabilities, and that improved power to weight ratios contribute significantly towards this goal, it is unlikely that substantial further improvements are to be expected. On an equivalent-maximum-engine-power basis, one must expect that a diesel engine (plus its auxiliaries) sized for a 3500 lb. intermediate size car, with typical U.S. passenger car performance characteristics, would be between 150 and 300 lb. heavier than an equivalent horsepower gasoline ICE. [42]

It is unclear whether the use of a turbocharged diesel engine significantly affects this weight penalty. Two alternative engine evaluations assessed the turbocharged engine as superior to the naturally aspirated engine in the passenger car application. [7,8] However, Ricardo (42) completed a preliminary design of both types of an indirect injection engine (a V-8 naturally aspirated 150 hp engine and a turbocharged in-line 6 150 hp engine) and found little difference in engine weight. The question remains unresolved, but probably does not significantly affect the relative attractiveness of the diesel.

The greater engine weight for equivalent power to the gasoline engine, and the noise and vibration characteristics of the diesel, all impact on the engine-vehicle integration process. At issue is whether substantial vehicle redesign would be required if the diesel engine were manufactured and marketed in U.S. passenger cars. Choices made here

strongly influence the costs and risks associated with the introduction process. The less important of these factors are the noise and vibration characteristics of the diesel engine. It has been the experience of manufacturers of current production diesel passenger cars that several years of engineering effort at the product improvement stage are required to reduce noise and vibrational levels inside the vehicle to close to gasoline engine vehicle standards. Thus, one would expect that, at introduction, diesel cars would be noisier and suffer more from vibration than the vehicles they might replace. The market implications of this are unclear.

The most important trade-off in the engine-vehicle integration process is between vehicle acceleration capabilities, and the fuel economy and the initial cost of the diesel vehicle, relative to an equivalent gasoline ICE vehicle. For roughly equal engine displacement, as is the situation with currently available diesel cars, vehicle acceleration is substantially inferior. As the diesel vehicles' acceleration is improved, both the engine weight and the vehicle body weight increase; fuel economy worsens due to both the increase in vehicle weight and due to increasing ratio of engine maximum power to average power required for normal driving. Vehicle initial cost increases. We will now establish the rough magnitude of the trade-off between diesel vehicle fuel economy and acceleration, relative to the baseline ICE vehicle.

Our goal is to calculate the ratio of the diesel vehicle fuel economy, to the fuel economy of an equivalent gasoline ICE vehicle (with both fuel

economies expressed in miles per gasoline-equivalent gallon (i.e., miles per unit energy content in the fuel). Our equivalent vehicle definition is that internal compartment size, tank mileage, and the choice of key power-consuming accessories have been held constant in the comparison. But, in contrast to the Stirling engine assessment where vehicle acceleration was held constant, we will here allow the displacement of the diesel engine to increase from being roughly equivalent to the ICE¹ (where the diesel's acceleration is significantly inferior) to the point where the diesel and ICE vehicles have equal acceleration². We would like to make this comparison at an appropriate future date when reasonable numbers of diesels might be entering the market. Volkswagen and General Motors consider model year 1978 and 1979, respectively, as possible introduction dates for the diesel engines they are developing. We will use model year 1980 as a suitable evaluation date.

It must be admitted that the data available to quantify this trade-off are limited. We will use the JPL [8] evaluation of a "mature" diesel to establish the equal acceleration end of the curve. The JPL diesel technology -- a turbocharged indirect injection modified swirl chamber engine -- corresponds closely enough to what could be mass produced on about this time scale. The JPL study provides values for fuel economy of a range of diesel cars -- from subcompact to full size -- which have the same 0-60 mph acceleration times as their gasoline-ICE equivalent-size

¹In today's diesels compared with their gasoline engine equivalents, engine displacements are roughly equal and engine weights are slightly higher.

²This latter point corresponds to the "Otto-Engine Equivalent" vehicle in the JPL comparison. [8]

vehicle (which have performance equal to today's average values). We have normalized these diesel fuel economy values (average EPA cycle values expressed in miles per gasoline equivalent gallon to correct for the higher heating value of diesel fuel) with the average 1975 model year equivalent size gasoline engine vehicle fuel economy. The data point on the left of Figure 6.1 includes all these car sizes; apparently the scaling we are attempting is almost independent of car size. Equivalent assessments are not available to evaluate the lower acceleration end of the curve. We have used data from diesel passenger cars which have new or upgraded engine designs -- the Mercedes-Benz 240D, 300D; Peugeot S40D; and the VW Rabbit diesel prototype. Our rationale is that these vehicles represent the best diesel engine technology available today and it is our assessment that significant improvements for 1980 production are unlikely. We have normalized each of the average measured EPA cycle fuel economies of these vehicles (again miles per gasoline equivalent gallon) by the average fuel economy of an equal weight 1975 model year gasoline engine vehicle. We have normalized the actual diesel vehicle 0-60 mph acceleration times by the average 0-60 mph acceleration times of 1975 equal weight gasoline vehicles, as determined by JPL, to provide a relative performance measure. The points are shown in Figure 6.1; a straight line of slope -0.7 gives the trend. It can be argued that by 1980 these vehicles may have improved engine efficiency and/or acceleration. Since these are all new or updated engines, we believe these improvements would be modest¹, and they would increase the slope of the trade-off line.

¹The JPL mature diesel technology is only marginally better than the present diesel technology.[8]

However, as discussed in Chapter 4, the ICE is a moving baseline. There, in Figure 4.1, we presented estimates of the fuel economy of ICE vehicles relative to a 1975 baseline at various emission levels. If we exclude the estimates for the 0.4 g/mile NO_x standard, because the diesel would not be certifiable at this NO_x level, the range in 1980 ICE fuel economy is from -7 to +18 percent change from 1975. The band in Figure 6.1 shows the impact of this uncertainty in ICE baseline on relative diesel vehicle fuel economy gain.

Two important conclusions can be drawn from Figure 6.1. First, that the choice of relative acceleration for the diesel significantly affects its relative fuel economy (going from roughly equal engine displacement to equal vehicle performance halves the relative fuel economy advantage). Second, the uncertainties in the ICE baseline fuel economy, which result from uncertainties in applicable emissions standards and in the technological gains which can be realized with the ICE, are of the same order as the fuel economy gains the diesel may achieve.

We must now address the question of whether comparable uncertainties exist in projecting the performance and efficiency of the diesel engine technology. Our assessment is that comparable uncertainties do not exist, for the following reasons.

The largest part of the ICE uncertainty, as it relates to the diesel, comes from uncertainty as to the applicable emission standards for HC (1.5 to 0.41 g/mile) and NO_x (3.1 to about 2 g/mile¹). Since the diesel meets the 0.41 and 2 g/mile HC and NO_x standards without any fuel economy penalty this uncertainty is not present. The second part of the ICE

¹We have assumed the 0.4 g/mile NO_x standard will not be implemented on this time scale.

uncertainty has to do with the magnitude of fuel economy gains obtainable from certain engine design and operating changes. These changes primarily relate to use of leaner mixtures, increased compression ratio, and improved control of engine operating conditions to reduce the impact of emissions and fuel octane constraints on engine efficiency (see Table 4.2). None of these changes are relevant to the diesel technology.

Thus, it is our conclusion that the diesel technology for the 1980 time frame is well defined and "mature" in the sense that the potential for significant improvements in attributes is not available. This does not mean the diesel is unattractive as an alternative engine. But it does mean that, even though diesel engines of the size and design required for the U.S. passenger car market are not readily available for testing, the characteristics -- fuel economy, acceleration, engine size and weight -- of engines and vehicles of appropriate size can be evaluated with relative ease.

The final part of this trade-off is diesel engine cost relative to the cost of an equivalent ICE. A number of factors contribute to the higher initial cost of the diesel engine. The fuel injection equipment is more costly than the ignition system and carburetor it replaces. The increased weight, more complex geometry of the engine, and greater use of more expensive materials are also important factors. Due to the higher compression ratio, closer manufacturing tolerances on some parts are required. Some of the accessories must be heavier duty. A first cost for the diesel of 1.5 to 2 times an equal maximum power gasoline ICE is a rough estimate of the diesel's initial cost disadvantage.. [42]

This equal power point is between the two extremes encompassed in Figure 6.1. At equal engine displacement, the diesel maximum power is less. At equal vehicle acceleration, the diesel power is greater because of its greater engine and vehicle weight. Thus, the initial cost penalty of the diesel relative to the ICE varies with relative acceleration. We will address the magnitude of these initial cost penalties more fully in the next section.

So far we have described the diesel engine technology which would be available for production in the U.S. by about 1980. We must also address the question of whether significant improvements in diesel engine attributes are possible in a longer time frame through major advances in the technology. One potential development is the use of ceramics for parts of the cylinder head, cylinder liner, piston (or piston crown). The goals in substituting ceramics for metal in these components are to reduce engine weight and heat losses. While success in developing suitable load-bearing ceramics would probably yield gains in these areas, almost equal gains would be realized by the use of the same materials in the baseline ICE so the relative position of the diesel would be essentially unchanged. [8]

Two other advanced diesel concepts are currently being examined: the variable compression ratio diesel and the ignition-assisted diesel. Direct-injection variable-compression-ratio diesels have been developed in larger than automobile sizes by the U.S. Army. High compression ratios are used at light load for maximum economy; progressively lower ratios are used as load increases to limit the maximum cylinder pressure. The

primary gain is claimed to be a reduction in engine weight; the principal penalty is in engine complexity; and the cost implications are unclear.

The second concept, a low compression ratio ignition assisted diesel is potentially attractive because the high compression ratio of current high speed diesels is used primarily for acceptable cold starting, and the prevention of high speed light load misfire and blue smoke after a cold start. A reduction in compression ratio does not affect efficiency, and reduced peak cylinder pressures could give reductions in engine weight and cost. One engine concept which would fall into this class is already under development by the U.S. Army -- the Texaco Controlled Combustion System fuel injected stratified charge engine. The performance characteristics of the diesel and an ignition assisted low compression ratio diesel (or one of the fuel injected stratified charge engines) are closely comparable on an equal performance vehicle basis. [8] However, the ignition assist aspect does release the diesel from its fuel cetane rating constraint (a requirement for acceptable fuel ignition quality), a point which might be of importance in the longer term and which we will examine below in Section 6.3.3.

We conclude, therefore, that while some of these advances may have modest implications on the initial cost penalty of the diesel, they appear unlikely to significantly change the diesels' fuel economy relative to the ICE.

6.3 Factors Influencing the Diesel Introduction Process

Summarizing the discussion in the previous section, the diesel can be characterized relative to the ICE as follows. The diesel engine has higher initial cost. For roughly equivalent engine displacement, the diesel vehicle has significantly lower performance; for equal vehicle performance, the engine and vehicle weight are higher than for the ICE. Between these extremes, there is a fuel economy advantage for the diesel, but the fuel economy advantage decreases as the diesel vehicle's performance increases to approach that of the ICE vehicle. There is also a possible fuel price advantage if diesel fuel remains cheaper than gasoline. The diesel emission levels in vehicles of similar weight are not significantly lower than reasonable projections for ICE vehicles with oxidation catalysts, but in the diesel low HC emissions are achieved without a fuel economy penalty. Diesel engine NO_x emissions appear unlikely to be controllable to levels approaching the 1978 0.4 g/mile standard. These are questions about whether other emissions from the diesel might be subject to regulation, if large scale production appeared likely, or occurred. Maintenance costs for the diesel are likely to be significantly lower than for equivalent emission controlled ICE's.

Furthermore, the diesel engine technology is highly developed -- existing light duty engines have evolved from previous engine designs as a result of substantial efforts improve their performance characteristics and marketability. Strong pressures to decrease the diesel's initial cost penalty relative to the ICE, and improve its fuel economy to offset that cost penalty, have always existed. The engine technology is "mature"; it is unlikely that significant improvements in its attributes, at least in the short term, can be expected.

In this section we attempt to evaluate the life-cycle costs of a mature diesel vehicle relative to an ICE vehicle, and examine under what conditions it would be most attractive. We then discuss the likely introduction process for the diesel should one of the major manufacturers make the decision to bring the engine into production. We will end this section by summarizing the nature of the barriers which we believe are currently holding back more extensive diesel development or introduction within the automobile industry. These barriers are uncertainties in some of the marketing aspects of diesel vehicles which will have different characteristics to the ICE, and most importantly the current situation with emission standards.

6.3.1 Total Operating Cost Estimates

Life cycle cost calculations relative to the ICE for the diesel are complicated by the substantial difference in specific power (maximum power per unit engine weight) between the two engines. Because of this difference, the choice of the relative acceleration capabilities of the two vehicles has an important impact on these cost estimates. Also, for a given interior compartment size the diesel vehicle will be heavier than its ICE equivalent due to both the heavier engine and influence of the heavier engine on the vehicle body -- a weight propagation effect exists. The fuels used by the two types of engine are different, and currently have a cost differential which is significant. And maintenance costs are likely to be different to an important degree. We will not attempt to construct a total cost model similar to that developed for the Stirling engine in Chapter 5, but we will now examine the impact of each of these points on total operating costs for the diesel relative to the ICE.

A number of estimates of the initial cost of a diesel vehicle with roughly the same acceleration as an equivalent size gasoline-ICE vehicle have been made. [7,8,53] The variation in diesel vehicle initial cost minus the ICE vehicle initial cost is so great -- from \$260 [8] to \$1000 [7] for (about) a 4000 lb. vehicle -- that these estimates must be used with caution. An important part of this difference in estimates comes in the different engine weight estimates (the diesel engine weight ranged from 140 lbs. to 240 lbs. heavier than the equivalent-performance (ICE), and the magnitude of the weight propagation effect (vehicle weight increases other than engine weight increases ranged from 50 to 300 lbs.)). We suspect that Rand [7] has overestimated the diesel vehicle body weight penalty since existing diesel vehicles can tolerate engine weight increases of the order of 100 lbs. without significant additional vehicle weight penalties. Also, an additional vehicle weight penalty in the 50-100 lb. range adds about \$50-\$150 to the initial vehicle cost, which is relatively small compared with differences in engine costs. We will, therefore, neglect the initial cost of increase due to vehicle body weight increase in the rest of our discussion.

Ricardo's estimate of diesel engine cost is useful to us in this context because it is expressed as a ratio to ICE cost. [42] Also, since Ricardo has extensive experience in both diesel and ICE design we expect their estimate to be reliable. They suggest that for equal maximum engine power the diesel engine (engine, auxiliaries and battery) will be 1.5 to 2 times the initial cost of the ICE baseline (about \$900 for a 150 hp engine, see Chapter 4). But as we consider engines of different sizes

which cover the relative vehicle acceleration range shown in Figure 6.1, this initial engine cost ratio will decrease as diesel engine maximum power falls below ICE engine power; and will increase as diesel maximum engine power increases to provide equal vehicle performance.

If we assume that engine cost scales with engine weight, and use JPL calculations of engine weight as a function of maximum horsepower [8], we can scale this diesel engine initial cost factor across this relative performance range. 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.

It is generally agreed that maintenance costs with the diesel vehicle are likely to be lower than with the ICE, primarily because the fuel injection system requires less attention than a conventional carburetor, and there is no ignition system. Though consumption of oil is higher [42], maintenance costs for 100,000 miles (supplied by Daimler-Benz) show a significant diesel advantage -- \$1,153 for the 240 diesel versus \$2,590 for the 2.3ℓ gasoline vehicles. [87] But NAS estimates [56] indicate smaller incremental lifetime maintenance costs for the diesel relative to the ICE at equivalent emission levels, of order \$100-\$200. But even if lifetime maintenance savings are only several hundred dollars, they still translate to savings of order several tenths of a cent per mile and are therefore significant in the overall cost evaluation (see Section 5.3.1.2).

The next factor to consider is the diesel fuel price advantage. Currently, diesel fuel has a cost advantage of 3-4 ¢/gal. relative to gasoline (and 0.88 gal. of diesel fuel are equivalent in energy content to 1 gal. of gasoline). This translates to about 0.2 ¢/mile operating cost advantage for the diesel vehicle. This diesel fuel price advantage reflects the lower production costs of the diesel fuel at current diesel to gasoline production ratios. Presumably, this price advantage would remain during the diesel engine introduction process, and as the diesel engine portion of the market started to grow. But, if the diesel fuel to gasoline ratio shifts substantially, then the fuel production cost advantage of diesel decreases. Thus, if diesel vehicles ever came to share the market roughly equally with gasoline engine vehicles, it is not clear the fuel cost advantage would be fully or even partially retained. While this is so far in the future and so speculative it may seem irrelevant, it does influence calculations of the long-term potential of the diesel as an alternative engine. We examine further the implications of much greater use of diesel fuel below.

From the results of the Stirling engine total operating cost advantage analysis presented in Figure 5.2, we can draw preliminary conclusions regarding the attractiveness of the diesel in terms of total operating costs. 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 1.5.¹ The expected range of engine initial

¹The engine and vehicle weight of the diesel and the ICE would be roughly the same, so Case 2 results shown in Figure 5.2 would be applicable.

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 assured. We, therefore, conclude that relative attractiveness of the diesel, on a total operating cost basis, is strongly dependent on the acceleration capability of the diesel relative to average ICE equivalent vehicles. Thus, the attractiveness of a diesel vehicle depends on a design choice which must be based on an assessment of the market appeal of a vehicle with significantly lower than normal performance.

Two factors could act to offset the above evaluation. One is the effective discount rate vehicle purchasers apparently use, which is higher than the 4 percent social discount rate used in generating Cases 1-4 in Figure 5.2. The gains from the reduced fuel and maintenance costs of the diesel might, in private calculations, only offset a much smaller initial cost penalty (see Case 5 in Figure 5.2). The second factor of importance is competition from a lower-than-average-powered ICE vehicle. ICE vehicles are available now with a range of engine sizes. If a sizeable market exists for a diesel vehicle with much reduced performance, than a comparable market may exist for ICE vehicles with much reduced performance. The lower-performance ICE vehicle would have lower-than-average initial

cost and higher-than-average fuel economy. It would not, however, realize savings through reduced fuel price and maintenance costs. JPL quotes a 15-20 percent fuel consumption increase for a 40-60 percent horsepower increase in ICE vehicles. Thus, a reduction to 0.6 of average acceleration (the acceleration of the roughly equal displacement diesel which has about 0.7 times the average ICE horsepower) would yield a 15-20 percent improvement in fuel economy. This would have the minimum projected fuel economy advantage of the diesel at this acceleration level.

We see that the relative total cost advantage of the diesel is strongly dependent on design choices determined by estimates of market implications of changes in vehicle attributes from the average values of today's automobile.

6.3.2 Introduction Constraints

We will presume for the moment that the diesel engine has been developed to the point where an automobile manufacturer sees it as an attractive product option. The nature of the process by which major product changes occur in the automobile industry is likely to constrain the type of diesel vehicle which the industry would produce, especially at the time of introduction. The analysis of the technology development and production process in Chapter 2 indicates that the diesel would be offered as an option to the conventional gasoline engine in an existing vehicle body, to which only the minimum of modifications would be made. This approach limits the funds risked in the diesel introduction process essentially to the capital invested in the new diesel engine production line.¹ Further,

¹The engine development costs are considerably smaller than this.

the capital investment in the diesel engine production line would also be held to a minimum by using as many common or standard gasoline ICE parts, and as much common production machinery as possible.

Apparently, this is the approach both Volkswagen and General Motors have adopted in their diesel engine development programs. VW has utilized its standard 1,475 cc gasoline ICE, and added a diesel cylinder head. GM is expected to use the block and other engine components from its 350 CID gasoline engine. Thus, the diesel vehicle, at introduction, will have an engine with roughly equal displacement to the gasoline ICE it replaces. The engine will have a slightly higher weight, which can probably be absorbed into the existing vehicle body in which it is being marketed with relatively modest body changes. It will have significantly lower vehicle acceleration than its ICE equivalent. However, the different diesel speed-torque characteristics can be taken advantage of to minimize the impact of lower engine power at more normal vehicle operating modes than wide-open-throttle acceleration. It will not, nonetheless, provide performance equal to the average ICE vehicle of equivalent size.

At this point, we want to stress that the manufacturers' incentives as the Introduction Decision is approached are different from the incentives of many in government and elsewhere who view the diesel engine as a means of achieving substantial national fuel conservation. The manufacturer, presumably, is solely concerned with whether the market is large enough for him to recover his investment in engine development, introduction and mass production costs. For the diesel, these costs and risks are only slightly higher than those associated with a new gasoline ICE. (The situation

for Stirling or gas turbine engines, for example, is very different indeed; changes to these other alternative engines represent "revolutions" in engine technology.) For the manufacturer, adequate return on his investment may be obtained with relatively modest market penetration.

If the introduction of the type of diesel vehicle described above is successful, the engine-vehicle combination will most likely be further optimized in the Mature Production Stage which follows introduction, as described in Chapter 2. Here, through evolutionary changes in engine and vehicle design, the attributes of the vehicle are modified to increase its relative attractiveness in the market. Daimler-Benz has moved to larger and more powerful diesel engines in its passenger cars in this stage of development to reduce the performance gap between its diesel and gasoline engine vehicles. While it seems likely that some movement in this direction would occur if the diesel introduction process were perceived as successful, it is not at all clear how far such efforts would go. Efforts to improve the performance characteristics of the diesel engine vehicle to more closely match its gasoline ICE equivalent would increase the initial cost penalty of the diesel, and decrease its fuel economy advantage, and not necessarily increase its market appeal. Thus, in our judgment the diesel is inherently a lower powered alternative to the ICE, and should be evaluated as such on a roughly equal engine displacement basis. One may speculate as to longer term future product improvement trends, but on that time scale one is doing little more than guessing.

6.3.3 Critical Uncertainties

In this section we will summarize the critical areas of uncertainty which we believe are currently inhibiting diesel engine development efforts,

and a resolution of any industry introduction decisions. First, however, we will address the question: Are there significant uncertainties in the performance, fuel economy and initial cost attributes of a diesel engine vehicle, using engine technology available in the short term, and given the constraints of the introduction process itself?

While it is not possible to find agreed-upon values for all these attributes in the open literature, we have concluded that the characteristics of the available technology are sufficiently well defined for this to be primarily a problem in scaling. Diesel engines are not now readily available with suitable displacement for testing in intermediate and full size U.S. cars. However, we judge that the cost of the design and development effort required to accurately characterize the attribute values of a diesel engine for a particular vehicle are modest in comparison to that required to characterize Stirling or gas turbine engine vehicles, and are only slightly higher than the cost of an equivalent new ICE development program. VW and GM are already well into such diesel design and development programs.

We conclude, therefore, that the primary uncertainties regarding diesel engine introduction are not in the vehicle's performance, fuel economy or initial cost. Rather they are in the potential of the diesel to meet the NO_x emissions standards of the future, the questions associated with currently unregulated emissions which might be subject to standards in the future, in the assessment of the market potential of the "low performance" diesel with its higher initial cost but lower fuel consumption.

fuel price and maintenance costs, which in turn is made uncertain by uncertainties in the attributes of the baseline ICE. We will now address each of these areas of uncertainty in more detail.

Emissions

The current uncertainty over the 1978 NO_x emission standard of 0.4 g/mile is a major factor in diesel engine introduction decisions. For example, GM Chairman Murphy has indicated that the absence of congressional action to resolve this issue and substantially delay or remove this requirement, would rule out the diesel as a mass production automobile engine for the foreseeable future. [94] The issue is complicated because many proposed changes in NO_x emissions standards are being suggested to, and considered by, Congress, and it is not at all clear what degree of resolution of the issue is required to make the introduction risk tolerable.

Roughly, three types of proposals have been suggested. One is the rapid reduction in NO_x standard to whatever level is selected as the strictest standard written into the law. There is now serious discussion of removing the 0.4 g/mile standard and replacing it with a higher one -- 1 g/mile is being proposed. There would undoubtedly have to be some delay in either of these ultimate NO_x standards because the gasoline ICE could not meet these requirements without additional successful development. The second type of proposal is a five-year moratorium, with NO_x standards at today's or slightly lower levels, with the longer-term future left vague because it isn't worth attempting to resolve right now. The third type of proposal attempts to lay out the standards for a fifteen-year time span -- EPA has made one proposal which defers the 0.4 g/mile NO_x standard to 1989. An

additional complication is the apparent need for a stricter NO_x standard in the Los Angeles basin than elsewhere, and the unknown degree to which future emissions standards will reflect these regional needs.

How long an assured future schedule of NO_x standards would be required to make the uncertainty with respect to diesel NO_x emissions much less important? (It is difficult to conceive of the issue being removed entirely.) Generally, in engine mass production facilities of the scale used by the automobile manufacturers, the investments in tooling and foundry equipment are written off over about ten years. It may be unrealistic to expect an assured emission standard climate over this time span. However, it seems reasonable to conclude that a five-year moratorium, to say 1982, with NO_x emissions above about 1.5 to 2 g/mile followed by several years with NO_x emissions at least no lower than 1 g/mile would be required to sufficiently reduce the risk associated with initial introduction. Significant market penetration, that is expansion of diesel engine production facilities beyond the initial introduction phase, might require a longer term assured emissions climate.

The problems associated with diesel emissions which are not now subject to regulation are poorly documented, and the implications of extensive diesel engine use have yet to be examined. Areas of concern, where standards might be introduced if diesel introduction on a large-scale was contemplated or occurred, are particulate emissions, odor, sulfate emissions, and perhaps NO_2 and aldehyde emissions. The concern is that these standards might be expensive or impossible to meet, and would therefore significantly alter the market appeal and profitability of a diesel vehicle

or even prevent its continued production. The magnitude of diesel engine emissions of these pollutants are not well defined; the potential impact of these emissions from large numbers of diesel on the urban air pollution problem, has not been assessed. And, the control technologies in these areas (in contrast to diesel engine NO_x emissions controls which have been subject to extensive R & D) are not well developed.

Marketing Factors

We have described how the characteristics of the diesel make it more attractive as a lower performance alternative to the ICE, and how the fuel economy and initial engine cost compared to the ICE all vary with the diesels' performance relative to average equivalent ICE vehicles. We have also explained how the nature of the introduction process pushes the diesel engine design to the low maximum-vehicle-acceleration end of the performance spectrum, since the greater the commonality in engine components and vehicle design with an equivalent existing ICE vehicle, the lower the initial capital investment required. A major uncertainty then is the market appeal of a diesel vehicle with these characteristics. The choice of relative maximum-acceleration-level is critical since that determines relative fuel economy and initial cost, and presumably market appeal.

The assessment of the attractiveness of the diesel compared with an ICE-equivalent vehicle is greatly compounded by the uncertainties in the ICE baseline. We have already indicated the magnitude of that uncertainty in Figure 6.1. A further uncertainty for the manufacturer is the appropriate discount rate to use in evaluating how vehicle purchasers would trade off increases in initial vehicle costs against reduced fuel consumption, most

likely a reduced fuel price, and potential reduced maintenance costs over the vehicle's lifetime.

While these uncertainties are formidable, there is almost nothing the government R & D planner can do about them. They are inherently questions which the automobile industry has to evaluate for itself, if diesel engine development or introduction decisions are to be resolved.

Fuel Availability and Cost

Unlike the Stirling, gas turbine and some stratified charge engines, which are multi-fuel engines, the diesel must use a fuel with a carefully controlled ignition quality -- characterized by a cetane number. From the marketing standpoint, two aspects of diesel fuel supply are important, particularly at the time of introduction -- cost and the question of widespread availability. We have already discussed the cost issue and concluded that in the short term, today's diesel fuel price advantage would probably be maintained.

In the long term, if widespread use of diesel passenger cars occurs, the continuation of the diesel fuel price advantage would depend on the availability of suitable amounts of diesel fuel without extensive refinery modifications. Currently, diesel fuel used in transportation is about one-tenth the total automotive fuel production. It has been argued that increasing the proportion of diesel fuel and decreasing that of gasoline would decrease energy losses in the refinery. Studies have been done to examine the implications of increasing the proportion of the diesel fuel fraction of the transportation sector petroleum demand, while continuing to supply the appropriate petroleum products to other sectors of the market

in quantities proportional to today's useage. There is some disagreement as to the maximum fraction of the transportation sector's fuel which can be diesel, at the optimum refinery operating conditions. One study claims that the 1972 fraction of diesel fuel used in transportation sector can increase by 70 percent before the optimum yield is reached. [95] Another study has indicated it is possible to achieve much greater increases in diesel fuel, as a proportional of total automotive fuel, with maximum savings in process energy at the refinery, relative to today's practice, of 2 percent occurring at about a diesel fuel to gasoline ratio for transportation of 1:1. For syncrudes, the optimum mix for minimum refinery energy losses is expected to be about 1:2, diesel fuel : gasoline. [96] There do not, therefore, appear to be major constraints of expanding the diesel fuel demand and maintaining the relative price advantage, though there appears to be some disagreement as to what the optimum proportions of diesel and gasoline would ultimately be.

The availability issue concerns the distribution of outlets for diesel fuel which now exist, and the impact that the more limited availability of diesel fuel might have on the initial market appeal of a diesel engine car. Especially in urban and suburban areas, diesel fuel outlets are much more limited in number than gasoline stations. This is obviously not an overwhelming impediment to diesel car sales, Mercedes and Peugeot diesel vehicles are saleable in limited numbers. But these vehicle buyers may be a very special part of the market -- they are buying a high priced, low performance, high efficiency vehicle. Of course, if diesels are introduced in significant numbers, the number of diesel outlets will increase. But at time of introduction, this may be a discouraging factor; and the diesel engine car cannot use gasoline in the introduction period as could

stratified charge, gas turbine and Stirling cars.

6.4 Government Involvement in Diesel R & D

In Section 3.1, we identified four objectives which Federal R & D programs might address: (1) advancing the state-of-the-art, (ii) supporting procurement; (iii) developing data for policy regulation and public information, (iv) providing "leverage" on private efforts. In this section, we will examine whether any of these types of Federally supported R & D activity are appropriate for the diesel, and if they are, what specific problems should be addressed. By appropriate, we mean that suitable government funded programs would contribute significantly to removing the uncertainty now surrounding passenger car diesel engine final development and introduction decisions.

Two of the above four objectives can be eliminated immediately. The government should obviously support diesel engine R & D related to special government procurement needs. The U.S. Army is already supporting diesel engine development for a number of its specialized vehicle applications (in the heavy-duty diesel field). Furthermore, given that light-duty diesels are already in mass production in Europe, and that one domestic automobile manufacturer, GM, and one foreign manufacturer, VW, already have extensive diesel engine development programs, it is hard to see any government program having significant additional leverage. We will now address the two remaining objectives for Federal R & D.

6.4.1 Advancing Diesel Engine Technology

Suppose the government mounted a substantial program with the goal of developing and demonstrating an automobile diesel engine of suitable size

for intermediate and larger size U.S. cars. Would the attributes of diesel as an alternative engine be likely to improve significantly? Would the automobile industry's information base with which to evaluate either the Final Development or Introduction Decisions be enhanced? We have concluded that the answer to both these questions is no, for the reasons we will now summarize.

We have explained that diesel engine technology available for introduction within the next five years is already highly developed; it can be characterized as a "mature" technology. It has gone through many product improvement phases -- for example, Daimler Benz had progressed through thirteen different model designations and a total production of more than 1.37 million diesel vehicles prior to the introduction of its new five cylinder 300D engine. Because of the diesel's lower specific power and higher initial cost than the ICE, strong pressures to achieve improvements in these two areas have always existed. Further, passenger car diesel engine development efforts are continuing, both in the European and U.S. automobile industries at a level far in excess of any program the U.S. government might fund. We conclude, therefore, that a Federal program with the goal of improving the attributes of automobile diesels for introduction within a five-year time scale is not likely to have a significant impact.

A somewhat better case can be made for Federal support of activities in the Initial Development Stage related to advanced diesel engine concepts. Current R & D activities on ceramic materials for reciprocating engines, on comprex-type superchargers, and low-compression ignition-assisted engine concepts are modest. A careful evaluation of the impact of the more

promising of these advanced concepts, on the diesel's attractiveness relative to the ICE, should first be carried out. While these are highly speculative areas, the costs of stimulating greater activity are not that substantial.

6.4.2 Public Policy and the Diesel's Emissions

We have described how current uncertainty as to whether diesel passenger cars will be able to meet future light-duty vehicle emission standards is inhibiting diesel engine development efforts, and especially the resolution of the Introduction Decision. It is most important to add that while a part of this uncertainty lies in precisely what the emissions characteristics of diesel vehicles would be, the greater part lies in what the applicable future emissions standards will be. We can divide the problem into two parts: the applicable NO_x emission standard; and emission standards for current unregulated emissions. We will argue that Federal research in these areas could contribute substantially to removing much of this current uncertainty that exists regarding diesel emissions. Indeed, the government has an obligation to act in this area and ought, with a high degree of urgency, to generate the necessary information to help resolve these policy issues.

The NO_x standard issue is paramount. It is almost unbelievable that, in the five years that have elapsed since the 0.4 g/mile was written into law in the 1970 Clean Air Amendments, the Federal government has not sponsored substantial programs with the goal of developing the necessary information which either gives this standard -- 0.4 g/mile -- a respectable scientific basis or supports an alternative. The original basis for this number [97] has been shown to be inadequate. Several independent studies

have carefully documented the need for a rational review (e.g., [75 , 98]. The implications of substantial errors in this number (as in the HC emission standard also) for the ICE are enormous. With automotive air pollution damages at the uncontrolled vehicle level assessed as having a total annual cost in the U.S. of \$2-10 billion [75], inadequate control could result in continuing damages on the order of \$1 billion per year. Excessive control could result in fuel economy losses for the ICE of order 10 percent or more (Figure 4.1), which could translate into \$2-3 billion per year additional fuel costs on a nationwide scale. For the diesel (if it in fact proves to be an attractive alternative to the ICE), an unnecessarily low NO_x emission standard could have the following impacts. It may either force substantial degradation in vehicle fuel economy (the diesel like the ICE suffers from a trade-off between efficiency and NO_x emissions if the fuel injection timing is retarded from its optimum position to achieve additional NO_x control); may limit diesel engine usage to small vehicles (because diesel NO_x emissions increase with increasing engine size) where the fuel savings per vehicle are less; or may prevent the introduction of the diesel altogether in the passenger car market. Each of these results would represent fuel conservation actions foregone, of sizeable impact (see Table 6.1 and Figure 6.1).

The type of research programs required to make progress in this area are substantial in scope and difficulty. The areas in need of much better resolution are the following. The magnitude and the uncertainties in aggregate vehicle emission characteristics, and in the relative contributions from mobile and stationary sources are not adequately characterized; the influence of meteorology and atmospheric chemistry on ambient air quality

are not at all well understood. The relative importance of HC reductions and/or NO_x reductions needs extensive investigation. The regional nature of the problem with the Los Angeles Basin as the worst case -- and a special case -- must somehow be incorporated into policy-making in a more rational way. Finally, the basis for the ambient oxidant and NO₂ air quality standards are subject to question.

It has been argued that substantial progress in resolving these uncertainties may not be achievable. Since the magnitude of efforts devoted to these areas to date has been relatively modest, we doubt that to be the case. Unquestionably, considerable residual uncertainty will remain but the identification of where that uncertainty lies, an understanding of the magnitude of that uncertainty, and above all an acknowledgment that uncertainty exists would be a substantial improvement over the current situation where a standard without any adequate scientific basis is regarded in Congress and in parts of the government as if it had such a basis.

It seems astounding to have to say that the Federal government should spend a few millions of dollars to help resolve uncertainties in NO_x standard definition where errors (either way) may cost billions. But until programs with this goal are completed, and the information generated in such programs used to develop a more rationally based schedule of NO_x emission standards, uncertainty as to what future light-duty vehicle standards will be, will continue to inhibit automotive engine development, and especially diesel engine development and introduction.

The characterization of diesel passenger car emissions for all pollutants which might be of concern, and the study of the potential impact diesel use on a wide scale might have on urban air quality, because of its different

emissions from the ICE, are also appropriate and important areas for government funded research. The controversy associated with sulfate emissions from catalyst-equipped ICE vehicles -- discovered after commitments to large-scale production of catalysts had been made -- is a continuing reminder of a situation to be avoided by prudent planning of research activities. A series of programs to quantify more precisely the levels of emissions from diesel vehicles of different sizes should be undertaken.¹ These emissions should include both regulated pollutants (HC, CO, NO_x), and other pollutants which may be of concern (particulates, SO₂, sulfate, NO₂, aldehydes). Odor is a problem where definition and characterization are important.

Once vehicle emission levels are better defined, impact studies should be carried out to determine if regulation would be necessary in the event diesels were used on a wide scale, and the approximate reductions in emissions required to hold the potential impact to tolerable levels should be assessed.

Should such studies show that substantial reductions might be required, then government funding to stimulate the development of suitable emission control technology might be appropriate.

6.5 The Diesel Engine: Summary and Conclusions

In this chapter we have examined the status of diesel engine technology as a potential alternative to the ICE in U.S. manufactured passenger cars. Both the technology which would be available by 1980, and more advanced concepts were considered. The attractiveness of the diesel relative to the

¹Several sizes of vehicles are now available for testing, either by the government or the automobile industry. These range from subcompact (the VW Rabbit), through compact (Peugeot, Daimler-Benz), intermediate (Chrysler has been testing a Valiant with a six cylinder Nissan diesel) to full size (Oldsmobile V-8 350 CID diesel).

ICE was determined through an approximate assessment of benefits expected in total vehicle operating costs. The major areas of uncertainty which currently inhibit diesel engine development and/or introduction were then identified as market appeal and inability to meet future emission standards. The degree to which Federal R & D programs could decrease the importance of these uncertainties was examined.

The attributes of the diesel engine can be characterized relative to those of the ICE as follows. The diesel engine has lower specific power than the ICE, 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 fuel economy advantage for the diesel, but the advantage decreases significantly as the diesel vehicle's performance approaches that of the equivalent-size ICE vehicle. The diesel offers potential advantages in lower fuel price and maintenance costs. The initial diesel engine cost is always higher than an equivalent ICE; the increase being greatest at the equal vehicle performance end of the spectrum described above.

This diesel engine technology which could be introduced within a five-year time scale is well characterized and highly developed. It is the product of many years of light-duty diesel engine development. Given the choice of relative acceleration level for the diesel, it is our conclusion that the diesel vehicle attributes can be estimated with reasonable certainty

with relatively modest effort, and a suitable diesel engine could be developed with a development program comparable in scale to that required to bring a new ICE into production.

An approximate evaluation of benefits to be gained through reduced total vehicle operating costs if diesels are substituted for ICE's indicates that gains of the order of several tenths of a cent per mile are realizable at the roughly equal-engine-displacement end of the relative performance range. At equal vehicle acceleration, gains are uncertain and are not likely to be realized without substantial fuel price and maintenance cost savings. Thus, the diesel engine is most attractive as a substantially lower power alternative to the ICE, i.e., at a substantially lower than average vehicle performance level.

The nature of the industry's technology development and production process also constrains the size of the diesel likely to be introduced as an alternative to the ICE. To hold investment in the diesel vehicle production line to a minimum at time of introduction, the diesel is likely to be installed into an existing vehicle body with only modest body design changes being made to accommodate the new engine. And it is likely to share many common parts and production machinery with the ICE from which it was developed. Thus, the roughly equivalent displacement diesel, with its modest vehicle body impact, holds the production costs at a minimum also.

One major uncertainty regarding the attractiveness of the diesel to the manufacturer is, therefore, the market appeal of a significantly lower than average performance vehicle, with a higher initial cost, which over the

vehicle's lifetime is likely to be offset by fuel and maintenance cost savings. The key questions here are customer evaluation of this trade-off and the potential size of the market for this type of vehicle.

The other major uncertainty is diesel engine emissions. Diesel vehicle NO_x emissions increase as vehicle size increases. The most effective control -- retarded injection -- brings with it a fuel economy penalty. Current uncertainty as to the fate of the 0.4 g/mile 1978 light-duty vehicle NO_x standard and the value and scheduling of its presumed replacement now inhibit passenger car diesel engine Development and Introduction Decisions. It is generally acknowledged that the diesel is most unlikely to approach this level of NO_x control. In addition to uncertainties in meeting NO_x standards, the diesels emissions of particulates, SO_2 , sulfates, aldehydes and NO_2 are, or may be, higher than ICE vehicle emissions, and may be subject to regulation if widescale use of diesels appeared imminent or occurred. There is real industry concern at the risk involved in investing in the production of a new engine technology which may well not be able to meet future emission standards.

The greatest areas of uncertainty we have identified are the market appeal of the diesel with its different attributes to the ICE, and the diesel vehicle's ability to meet future emission standards. The uncertainty as to the attributes of the ICE with which the diesel would compete compounds the difficulties in the diesel engine evaluation. In contrast, we judge the values of the diesel engine attributes, once the design performance level is selected, to be relatively certain, and not especially difficult or costly to confirm in a development process similar in scope and scale to that required to introduce a new ICE.

Thus, we argue there is almost nothing to be gained from a Federally funded diesel engine development program. GM and several European manufacturers are already involved in such programs at a level of development and program scale well in excess of what any Federal program might achieve. Current interest in the diesel is not constrained by difficulties in the development of the technology, and advanced diesel technology offers the promise (to date) of only modest further improvements. But, we also argue that the Federal government has a critical role to play in reducing the uncertainties associated with the diesel's emissions. First, the light-duty NO_x standard must be put on a sounder scientific base through substantial Federally funded programs which better define the relationship between vehicle NO_x emissions and ambient air quality. The costs of such programs are modest (of order millions of dollars) in contrast to the social costs of too much or too little control of vehicle NO_x emissions on a national scale (of order a billion dollars per year). It is astounding that five years after this NO_x standard was promulgated that efforts in this direction have not been initiated. Finally, the diesel's emissions of currently unregulated air pollutants must be characterized, and the potential impact on urban air pollution of widespread diesel use assessed. A repeat of the sulfate-catalyst controversy where additional air pollution hazards were detected after large-scale commitments to the production and use of catalysts had been made must be avoided.

The residual uncertainties which remain -- the market appeal of the diesel, and the values of future ICE attributes -- belong within the U.S. automobile industry, since Federal R & D on the diesel can have no impact on these areas.

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7. THE ELECTRIC VEHICLE

7.1 Introduction

Electric automobiles were a significant factor in the infant automotive industry of 1900, and it is conceivable that they will be important again by the year 2000. As with the alternative heat engines, the prospect is contingent upon the cost of liquid fuels and on the success of R & D efforts, in this case with the critical R & D focused on the batteries for energy storage rather than on the motor.

However, in the case of the electric car, the analytical difficulties described in Chapter 3 take an extreme form. Indeed, at this time and very probably for at least a few years in the future, support for the electric car option might best be thought of in terms of insurance against a hopefully avoidable set of difficulties, rather than (as in the case of alternative heat engines) as an investment with a well defined payoff as a function of assumptions about fuel costs, fuel economy, and engine costs.

What makes this investment/insurance distinction significant is not that the R & D program in support of electric cars is technically much more risky than in the case of radical heat engine alternatives such as the Stirling engine described in Chapter 5. That may be true, but certainly is not obviously true. Rather, the problem is that even if the R & D effort is technically successful, in terms of the crucial criterion of Chapter 3 (life-cycle cost), there may nevertheless be no significant market for electric cars. For an electric car, with technology that can be reasonably anticipated within this century, will not be simply a car with an electric motor rather than a conventional engine under its hood. It will be a car which is different

from a conventional car in ways which limit what the driver can use it for; in particular, it will be limited in practical operating range.

Consequently, a fundamental point stressed in Chapter 3 does not apply to the electric car. It is not true that even a slight improvement over the economics of a gasoline engine could produce a large social benefit, given the large number of vehicle miles driven each year. For a saving of a few tenths of a ¢/mile -- amounting to a few tens of dollars per year for the typical driver -- is not likely to be very interesting if it must be obtained at the "non-pecuniary" but very real cost of even occasional inconvenience due to the range limitation of the vehicle. Even savings of the order of a penny or two per mile may be insufficient to "sell" electric cars unless the R & D efforts are so successful as to make the range limitation of the vehicle a minor inconvenience to the driver.

On the other hand, there is an essential sense in which the electric vehicle option is potentially more important to the nation than the alternative heat engines. For in the event of severe constraints on the availability of liquid fuels by the end of the century, the electric car, which uses no liquid fuel at all, could have enormous social value.¹ The range of electric cars is likely to be significantly restricted by technology for at least the balance of this century. But this may come to seem rather unimportant should it turn out that the range of conventional cars must be limited by shortages of fuel. Given dwindling supplies of domestic petroleum, uncertainty about

¹If electric cars in large numbers were to be marketed within the next few years, the statement that they use no liquid fuel would be misleading; a significant fraction of the electricity they use would be provided by oil-fired generating plants. But by the end of the century, this is unlikely to be true, particularly in the event of severe liquid fuel constraints.

overseas supplies, and quite possibly practical limitations on synthetic fuel production, this is a prospect which -- while hopefully avoidable -- is hardly to be prudently ignored. It is as insurance against this prospect that the electric car option has peculiar importance.

The assessment of government support of the electric vehicle (EV) option we want to reach in this portion of the study will depend upon:

1. The social value of EV's.
2. The acceptability of EV's to users.
3. The prospect that increased government R & D on EV's will significantly speed up the evolution of EV technology.

By "social value" we mean what economists call the "external benefits" of EV use: the benefits that accrue to society as a whole;¹ "acceptability to users", in contrast, turns on the value of an electric vehicle to an individual user -- particularly the value of the EV compared to the value of an equal cost conventional car.

All three of the issues interact with each other. The social value of EV's can be realized only if such vehicles actually take over a significant portion of the automotive mileage, which in turn depends on the prospect that significant numbers of users find the electric vehicle an acceptable substitute for the conventional alternative. However, the reverse is also true. If it were judged important to the country to encourage the use of electric vehicles, then there would be a case for government policies (subsidies, regulations, etc.) which might stimulate use of electric vehicles even though (under free market conditions) EV's would be unattractive to users.

¹Note that this contrasts with the definition of social benefits as used in Chapter 5, which included both private benefits and external benefits.

So the question of how good the EV has to be depends on how strongly government policy intervenes in the market, which in turn depends on how highly a shift to EV's is socially valued. Finally, judgements about whether the pay-offs from Federal support for R & D justify the costs depends on both issue (1) (even if the probability of success is low, if the value of success is very high, one may wish to gamble), and on issue (2) (the probability of success will depend on how much progress over the existing state-of-the-art is required to make a significant improvement in the EV's acceptability to consumers). In the final analysis, all three questions have to be considered simultaneously. But is convenient to treat the questions separately until the final stage of the analysis.

We will start (Section 7.2) with a summary of the technical situation. We then address (Section 7.3) the question of the social value of an EV option. We then address (Section 7.4) the issue of user acceptability, attempting in particular to clarify the relationship between user acceptability and the driving range of the EV. (In part this depends on clearly distinguishing among various possible markets for electric vehicles; even more it depends on probing the relationship between driving ranges and the perceived needs of various classes of potential EV users). We next review (Section 7.5) the R & D situation bearing on electric vehicles, with particular attention given to the problems in high performance batteries. Finally, then, we are able (Section 7.6) to provide some conclusions on the role of Federal policy in support of EV R & D. These conclusions are likely to seem disappointing to advocates of a strong effort on EV's: for it proves to be easier to describe efforts which are likely to be futile, or even counter-productive, than to define areas where expanded Federal efforts are clearly important. On the

other hand, even the rather modest near term efforts that seem warranted add up to a program which is substantial compared to the current Federal rate of investment, and which could lead to much stronger Federal programs in this area before the end of the current decade.

7.2 Status of the Technology and Current R & D Programs

As is now widely understood, the fundamental technical problem facing the electric car is the limited energy storage capacity of batteries as compared to liquid fuels. As a consequence EV's, at least with current technology, are much heavier and more expensive than comparable conventional vehicles, and are severely limited in range. The following background points on the technology and economic prospects of electric cars develop this central issue.¹

7.2.1 Technology and Economics

The energy storage per unit of storage system weight (specific energy) of any battery depends on the power output for which the battery is optimized. This means that an EV design problem is encountered which is fundamentally different from that faced in a conventional vehicle: the energy content of gasoline is independent of the power demanded of the engine. It is a minor design problem to arrange to pump fuel to the engine at the rate desired. That is not the case for a battery. The more rapidly one wishes to draw out the energy -- i.e. the higher the power required -- the less the total energy which can be withdrawn. It is as if, in a conventional car, an increase in engine power were permitted only if the size of the fuel tank

¹Two useful systems studies and reviews of EV technology which we will not reference in the text are [99 & 100].

were reduced.

The problem of the power/energy trade-off has two implications important for the analysis which follows. First, the specific energy of a practical car battery (that is, a battery designed to handle power demands that must be faced in hill-climbing and acceleration) will be designed low compared to that of a battery using the same technology, but designed for a use under a uniform, low-power, duty cycle. Second, even after the battery has been optimized (i.e. designed and manufactured) for automotive use, the effective energy on a particular charge can vary widely, depending on how severe the demands for power turn out to be on a particular day's use. Factors which increase the power required -- hills, headwinds, etc. -- reduce the range not only by increasing the energy consumed per mile, but by effectively reducing the total energy which can be drawn from the battery, due to the power/energy trade-off.

Both points will be developed further in later sections of this chapter. An immediate consequence, though, is that one must treat paper design studies of EV's with special caution, since there are numerous subtle interactions (such as the power/energy trade-off highlighted above) that can make a vehicle which seems quite practical on paper quite impractical in practice.

Nevertheless, it is useful to have some rough quantitative feeling for the basic technical and economic prospects. A practical battery must provide the car with performance reasonably comparable to that of a low-powered conventional car, if only to avoid safety hazards. Table 7.1 gives some representative values for estimated maximum practical values for several widely discussed candidates for electric vehicle propulsion as compared to gasoline. The first column gives energy stored per pound; the second column then adjusts the base number to take account of the efficiency advantages of an electric

Table 7.1

COMPARISON OF ENERGY STORAGE IN BATTERIES AND GASOLINE TANKS

	Specific Energy (watt-hours/pound)		<u>Comment</u>
	<u>Base</u>	<u>Adjusted</u>	
Gasoline (includes tank, etc.)	1,130	140	Current state-of-the-art
Lead/acid battery	20	15	Probably achievable with near-term R & D
Nickel/zinc battery	50	35	
Lithium/sulfur battery (design goal)	140	100	Long-term goal for technology now under R & D

Note: Column 1 from [101]. Energy efficiency of conventional cars varies from 10-15% depending on driving conditions. A factor of 12.5% is used in the adjustment. EV efficiency is much higher, mainly because thermodynamic inefficiencies are absorbed at the generating plant, not in the vehicle; partly because no energy is used during idling. A factor of 0.7 is used here.

motor over a heat engine. It is the second which provides a reasonable comparison. However, even after this necessary adjustment is made, gasoline retains an advantage over the best projected battery performance. And a gas tank can be refilled in a few minutes; a battery recharge takes several hours.

The lead/acid battery is the familiar technology now used for starter batteries in conventional cars and for propulsion in specialized vehicles such as golf carts. The nickel/zinc battery is representative of technology which is roughly in the position of the Stirling technology discussed in Chapter 5: that is, likely performance is reasonably well defined, and R & D is focused on improving the economics of the technology. In contrast, the lithium/sulphur battery is representative of a number of advanced battery developments, for which achievable performance in practical applications remains quite uncertain. Initial vehicle applications of the advanced technologies is unlikely before the mid-1980's; and attainment of the long-run goals cited in Table 7.1 (if indeed they prove practical) lies even further in the future.

We can see that except for advanced batteries, the limited potential energy storage directly implies that a vehicle with range at all comparable to the "tank-full" range of a conventional car will be heavy, and the batteries massive and hence expensive.

In Table 7.2 estimates, adapted from the most recent detailed EV study, are given, based on (perhaps optimistic) estimates of future battery performance and costs obtained from battery developers. By making still more optimistic assumptions about such things as achievable cycle life, required vehicle range, and so on, it is possible to develop more optimistic numbers

Table 7.2

ESTIMATED COSTS FOR ELECTRIC VEHICLES

<u>Power Source</u>	<u>Cost¹ (¢/mile)</u>	<u>Comment</u>
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¢-\$1/gallon (including tax). The numbers are in 1973 dollars [103, Chart 10].

for the near-term (lead/acid and nickel/zinc) technologies. But we believe the above estimates in Table 7.2 for EV's are most unlikely, in practice, to turn out to be unrealistically high. The contrary is more likely. It must be stressed that the numbers for the conventional car are "real" numbers, based on demonstrated technology, while the numbers for the electrics depend on estimated costs of cars which do not yet exist, and in particular on estimates of the costs and performance of batteries which have not yet emerged from the laboratory. The numbers are particularly soft for the high temperature batteries, which are furthest from practical application.

In terms of such crude and perhaps (but not necessarily) overoptimistic paper estimates, and neglecting the problem of range, the advanced batteries look potentially interesting in term of economic competitiveness with conventional cars. And in terms of insurance against the possibility of severe liquid fuel constraints by the end of the century, investment in advanced battery technology looks very promising. On the other hand, these same numbers present a discouraging picture of the prospects for electric cars based on either lead/acid or nickel/zinc technology. Even before taking account of the effect of range limitations on the value of the vehicle, such cars look expensive compared to comparable conventional cars even at fuel costs substantially higher than today. And unless all of the various advanced battery programs fail badly, such cars would be markedly inferior to newer technology electric cars in the event of severe fuel constraints towards the end of the century.

Finally, we emphasize that the economic estimates of Table 7.2 refer to private passenger cars. The economic prospects of lead/acid or nickel/zinc powered vehicles are considerably more favorable, though, if one considers

specialized applications such as urban buses, delivery vans, and the like. This point is developed in Section 7.4.

7.2.2 Current Vehicles and Programs

In the light of this discussion, the most important point to note about existing R & D programs on batteries is that work on the high temperature batteries has been pursued for some years, primarily motivated by the importance to the electric power industry of developing reasonably cheap ways to store electricity for load-leveling. Consequently, the most important aspect of EV technology has been receiving support as a by-product of interest in improved batteries for other purposes. The crucial policy question is whether there is justification for expanding these efforts on advanced batteries; or for promoting efforts on nearer-term technology (notably, lead/acid and nickel/zinc) as insurance against the risk of severe liquid fuel shortages despite the unappealing economics suggested by the estimates of Table 7.2.

A candid report on electric passenger cars currently on the market, from a source unlikely to be suspected of any bias against EV's is provided by [103]. A wider survey of current vehicles is provided by [104].

7.3 Arguments For and Against EV's (Social Value)

Would an option to replace a substantial fraction of conventional vehicles with electric vehicles be socially valuable (leaving aside for now the benefits and costs to individual users, except insofar as they affect the practicality of marketing EV's, probably a sine qua non for obtaining

any social benefits)? A widely held view today, as reflected for example in Congressional support for EV demonstrations, is that such an option would be very valuable; but a contrary case can be made. We briefly review pros and cons of this question.

The fundamental element of the prospective social value of EV's is the prospect of reducing the national requirements for liquid fuels. Roughly 75% of all automobile mileage is accumulated on trips of less than 50 miles. More than half of all trips, although barely more than 10% of all mileage, are less than 5 miles. [73] Thus a large fraction of mileage is for travel which might plausibly be managed with a range-limited electric vehicle, and most of this short distance travel is within the urban areas in which most Americans live. A reasonable "ballpark" estimate of the travel which might be handled by electric vehicles would be to assume that EV's are substituted for second cars in urban households owning more than one car. Currently, something like 20% of all cars fall into this category. (About 30% of all cars are today owned by households with two or more cars, not all of which are in urban areas.) And barring continuing economic stagnation, that fraction will certainly increase. So, in principle, quite a substantial fraction of mileage could be handled by electric cars. But the conservation of liquid fuel is not the only gain that might come with an EV option. One may also consider possible gains in terms of reduced automotive emissions; the value of laying the basis for eventual much wider use of EV's (not only for urban travel); and improving the economics of an increasingly electric economy by providing a market for off-peak power. (The latter point depends on the assumption that an increasing fraction of electricity will be generated by nuclear power, where the high ratio of capital to operating costs in the total

cost of electricity makes it important to be able to run the plants close to 24 hours a day.)

To reach some judgement on the social value of these various potential payoffs from an EV development effort, it is necessary to consider at least the following offsetting arguments:

1. A variety of fuel options (e.g., syncrude, shale oil, etc.,) have been proposed that, for a long time at least, may be preferable to electric cars. One must assume very high cost for these substitutes for imported petroleum (certainly well above \$20/barrel-equivalent) and/or make very optimistic assumptions about the economies of EV's (i.e. approaching the long-run advanced battery goals of Table 7.2), to allow electric cars to provide transportation at a total cost per mile competitive with conventional cars. Yet unless electric cars are cheaper than conventional cars, why should consumers (and voters) be willing to use an electric car limited to the range of its batteries rather than a conventional car which for all practical purposes has unlimited range (considering the ease of refilling a gas tank compared to the time-consuming process of recharging a battery).¹ Except under extremely optimistic assumptions about EV's (or very pessimistic assumptions about the cost of synthetic fuel) the user could not expect to save more than a penny or two per mile. One can also not expect EV's, with their range limitations, to be driven more than 10,000 miles per year. Is it reasonable to expect that consumers would find saving a penny or two per mile (at most, \$100-200 per year) adequate compensation for the inconvenience

¹What about the possibility of quickly exchanging batteries? This appears to be a forlorn prospect for private cars. It is plausible, though, for commercial operations of a fleet of vehicles from a central base, where both the physical and bookkeeping operations for handling these heavy and expensive devices could be efficiently managed.

of a range-limited car?

2. Given current legislation on emissions, auto emissions will become a minor factor in urban air pollution. (This is the fundamental conclusion of the recent and widely cited EPA study of this matter.[101]) Replacing conventional urban second cars by EV's cannot make much of a difference.

3. The notion that EV's will fulfill a load-leveling role for the electric power industry is far from compelling, even if one ignores both the substantial grounds for skepticism that significant numbers of EV's can be sold and current uncertainties about nuclear power. Part of the problem is policing such an arrangement, since people are unlikely to wait until after midnight to plug in their vehicles for recharge. But this part of the problem could be dealt with by suitable, and probably not very expensive, gadgetry. A more important part of the problem is that, given the improvements in battery technology that would make EV's economically competitive, utilities could build their own load-leveling facilities. The batteries for the direct utility application (per kwh of storage) would certainly be cheaper than for EV use, though of course more expensive (to the utilities) than off-peak storage obtained as the by-product of EV usage. On net, considering all the factors, one may doubt that the presence or absence of EV's is likely to have any noticeable effect on the cost of electricity.

Our judgement is that this formidable list of objections, and it is simply unrealistic to ignore such objections, does not provide sufficient grounds to dismiss EV hopes as an illusion. They do, however, provide strong grounds for wanting to see any EV program carefully thought through and justified. Each of the objections has an answer, but always an answer that is only partial, not dismissive. Briefly,

1. On paper, substitutes for imported petroleum can be obtained at costs that would make the wide implementation of even a quite successful EV R & D program doubtful. But in fact, all of these options involve major economic, environmental, and political uncertainties. It is particularly doubtful that a large enough synthetic fuels industry will evolve before the end of the century so that one would not also value quite highly a complementary effort on EV's.

2. We cannot now foresee just how trade-offs between fuel economy and emissions control for ICE-powered vehicles will develop. EV's may well have a useful role to play in clean air strategy, particularly since their use is inherently concentrated in densely urbanized areas where the most severe air quality problems arise. Since the cost of auto air pollution controls is in the neighborhood of \$5 billion per year currently [], one should not dismiss the possibility that significant savings might be available if EV's were available as a component of a "two-car strategy".

3. EV's will probably not have an effect on electricity costs noticeable to the individual consumer; but since every household and firm is a user, even a minute effect can add up to many millions per year nationally.

How does one appraise the net situation? The fact is that any quantitative estimate is bound to be highly arbitrary; and in fact more useful primarily as an exercise for reaching a better understanding of the issues rather than for making specific decisions. Too much depends on political and technical developments in an uncertain future. Ultimately one reaches a cautious but affirmative judgement by a simpler and more intuitive process. Are there sets of circumstances in which we might plausibly seriously regret having made a substantial R & D effort to develop an EV option? It is hard to ima-

gine what they might be. The amounts of money are simply extremely small compared to the aggregate amounts -- currently exceeding \$100 billion per year -- spent on automotive transportation, reflecting the national importance of the system. Even a small probability of contingencies in which an EV option would be important will make "insurance" against such contingencies look prudent. And even total failure will have a trivial effect on our national performance in the transportation sector.

In contrast, it is easy to imagine circumstances in which the U.S. would seriously regret not having done what could reasonably be done to develop an EV option. One may merely note that interest in developing a "syncrude" industry continues despite rapid escalation of the estimated cost of syncrude. (Typical estimates are running in the neighborhood of \$20 per barrel compared to \$6-10 only two years ago.) Since few of these plants would be in operation before 1990, we are talking of a commitment to an expensive source of energy, with the commitment (given the capital investments required) running well into the 21st century. So long as this kind of commitment to syncrude is judged interesting, it is hard to imagine wishing to ignore an option which has at least the potential to be economically competitive, which may be environmentally and politically superior, and which, in any case, would complement rather than conflict with a syncrude program.

Thus the case for interest in an EV option does not turn on any particular calculation of its value, which for practical purposes may be made as high or as low as the analyst cares to make it. It is simply a matter of noting that it is not hard at all to construct alternative futures in which one would regret ignoring this option, but very hard to construct alternatives in which one would seriously regret having sought it.

Thus, it is even harder to make a calculation of EV payoffs than for the alternatives (such as those discussed earlier in this report) which involve less radical changes from the automotive technology we know today. This is scarcely surprising. It is always easier to specify the costs and benefits of small perturbations in a complex system than to foresee the costs and benefits of a radical change. But because EV's have the prospect of radically changing the system in a way which may prove to be critical -- namely disengaging an important, and ultimately perhaps even large, share of the automotive system from supplies of liquid fuel -- the potential payoff may be very important indeed. It is in this sense that we suggested at the outset that support for the EV option might best be regarded as prudent insurance, which is not likely to be regretted even should it turn out that it is not needed.

7.4 User Acceptability

Suppose then that we adopt the view that an EV option is, in principle, attractive, in the fundamental sense that if we look across the range of alternative futures, we find a number of contexts in which such an option looks valuable, and none in which we are likely to seriously regret having developed the option. We have only a rather empty conclusion. For the critical policy question regarding the EV's concerns the appropriate level of support (and balance between): a) near-term R & D and demonstration efforts to promote the development of an EV industry with technology that is currently available, or likely to become available within this decade, and b) support for R & D efforts on advanced batteries, looking towards applications in the late 1980's and beyond.

Other things equal, there is much to be said for moving expeditiously on encouraging the evolution of an EV industry. For although (in the light of the discussion of the previous section) the major payoffs from the EV option are likely to lie several decades off, the transition to substantial EV usage late in the century, if that proves practical and desirable, will be eased if a healthy and growing EV industry has developed in the interim, providing experience with the technology and at least the beginnings of the extensive infrastructure that would be required.

On the other hand, it is almost certain to be futile and self-defeating to attempt to promote the use of electric vehicles that are from the viewpoint of users (and voters), markedly inferior to conventional vehicles requiring either subsidies so massive or restrictions on the use of conventional vehicles so stringent that it is unrealistic to suppose that the program could (or should) command public support.

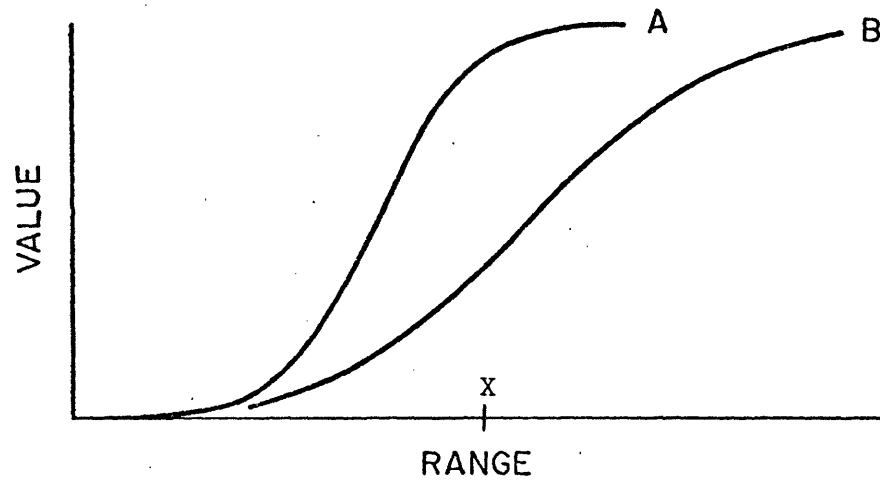
In this context, it becomes critical to consider, in particular, the relation between the acceptability of EV's and the practical range of the vehicle. For the acceptability of EV's will obviously depend not only on their cost, but on the extent to which they are in fact capable of replacing a conventional vehicle.

7.4.1 Range Versus Value

A convenient way to address the issue of user acceptability is in terms of a diagram such as Figure 7.1, in which the value of an EV (say, the ratio of the price it could command in the market to the price of a conventional car of comparable performance and size), would be plotted as a function of electric vehicle range. Even in the absence of data which would permit a

Figure 7.1

VALUE VS. RANGE FOR ELECTRIC VEHICLES



precise quantitative treatment, the figure provides us with a way of thinking about the problems of user acceptability.

The first thing to notice is that a value vs. range plot must, in fact, have the "s-shaped" form of the two illustrative curves in the figure. Obviously if the range is zero, the vehicle is of no value, and increasing the range from zero to some very low number will not greatly increase the value. Eventually, though, as range increases the vehicle becomes capable of handling typical trips the user has occasion to take. We reach a segment of the curve where value starts to increase rapidly with range. The probability that the owner will be unable to make (or worse, be unable to complete) a trip declines as range increases; accordingly the value of the vehicle increases. Eventually, the range becomes great enough so that it is only on rare occasions that the range limitation of the vehicle creates any concern for the user. We reach a "shoulder of the curve" beyond which the gain in value for successive increments in range becomes relatively small. If we assume -- and this is a sufficient approximation for our purpose -- that the user is indifferent between an electric and a conventional vehicle except for the issue of range, then the value of the EV will asymptotically approach the value of an equivalent conventional vehicle as range becomes very long.

For some distance beyond the shoulder of the curve, the EV is what we will call "almost competitive". It is not likely to be perceived by buyers as terribly inferior to a conventional car. It can serve ordinary needs quite satisfactorily. But it is still sometimes inconvenient. If (unsubsidized) costs of an EV were similar to those of a conventional car, one could imagine significant use of EV's given subsidies or regulations that

consumers (i.e. voters) do not regard as extravagant. Similarly, one can imagine significant numbers of buyers preferring such a car if gasoline shortages like those of the winter of 1973 become almost yearly experiences. But one can still hardly imagine a mass market for such a car if conventional alternatives are available at comparable prices, and if gasoline is almost always available.

We show the value of the car increasing only slowly beyond the shoulder of the curve. For although it is becoming less and less often that the owner finds the car can not take him where he wants to go, the effect of increased range will be modest. Changing the range of the vehicle from a few to 50 miles makes an enormous difference in the value of the car; increasing the range from 100 to 150 miles may make only a modest difference. There are still likely to be trips he would like to take (or even trips he merely wants the option to take) which are beyond the range of the car.

But although we can only expect value to increase slowly once the vehicle is capable of handling the great majority of trips, at some point further improvements in range will become sufficiently unimportant that our typical user finds the range limitation a minor factor in his choice between a conventional and an electric car. It is reasonable to suppose that this reduction of range limitation to a secondary aspect of the car's value will occur sooner if the car is a second car in an urban household, where another car is available for occasional long trips, than if the car is the one the household wants to use on weekends and vacations.

However, it does not similarly follow that the shoulder of the curve will be reached significantly sooner for a second car than for an only car. What data is available indicates little difference between the annual mileage

accumulated per car in single car and multi-car households. Except for occasional long trips outside the city, both the single car and multi-car household may turn out to have quite similar (urban) usage patterns and hence similar reactions to range limitations until EV's achieve sufficient range to comfortably handle the great majority of urban travel.

We would like to obtain some quantitative sense of what the range of an EV probably must be for the car to become "almost competitive". And we would like to reach some judgement as to when the range limitation, at least for a second car, might plausibly become a minor matter for many users, so that even occasional concern about fuel shortages, or such advantages of the electric as quiet operation and low maintenance, begin to seem as important to buyers as the fact that on rare occasions its range limitation is an inconvenience. In the former case, politically plausible subsidies or regulations may be sufficient to promote significant EV usage. In the latter case, EV's could be expected to achieve a significant market even if subsidies or other incentives were absent.

As a first approximation, we could assume merely that the value of the EV is proportional to the probability that it is adequate for a randomly selected trip. The range/value plot will be an s-shaped cumulative distribution curve (the dotted curve A in Figure 7.1). However, if in fact the EV is only interesting if it can satisfactorily replace a conventional vehicle the user would otherwise buy, then it will be only when the EV can handle most trips that we will begin to see a rapid increase of value as range increases. The steep part of the curve will be flattened somewhat, and the shoulder of the curve will be pushed out beyond where it would be under the simpler assumption (see Curve B in Figure 7.1).

An immediate application of this distinction is to the EV enthusiast who owns an electric car today. For him, there is no conventional substitute for the EV: an electric car is what he wants. His curve is Curve A. He may be very pleased with a car with a range at the point marked X. This in no way implies that the more typical user, whose preferences are given by Curve B, will find the EV even remotely competitive. This user will only find the EV attractive if someone else makes up the large difference in value between the vehicle with range X and the value of a vehicle that he feels really begins to meet his needs.

Similarly, suppose that at some future date households were permitted to own no more than one conventional car, or that severe gas rationing effectively makes it difficult to operate more than one conventional car; a second car must be electric or nothing. Under these conditions, Curve A is probably applicable: a car that can handle a large majority of trips may command almost as high a price as a conventional car. But in the absence of such severe restrictions, an electric second car which is adequate on 9 days out of 10 is a car that is inconvenient to own 2 or 3 days a month. A good used conventional car is likely to be preferable to such a car, and if so the buyer will not be willing to pay more for the electric than for the used conventional car.

We will see it is principally this distinction between the case in which the choice is an EV or nothing versus the case in which an EV must face competition from a conventional car that illustrates why we cannot reach the unqualified judgement that barring radical improvements in batteries, electric cars clearly can never find a market. If we are sufficiently pessimistic about the availability of liquid fuels late in the century, then

cars that would be marketable only to some minute fraction of buyers today may look quite reasonable to a wide class of buyers.

At the same time, though, one must note that for the foreseeable future, at least, severe restrictions on the availability of conventional vehicles are most implausible. For even given much more pressure for politically unpopular restraints on fuel use than is apparent today, it is hard to imagine that policies which effectively force the purchase of EV's (or nothing) would seem preferable to policies to sharply cut fuel consumption by severe taxes on car size and enforcing limits on speeds and performance. At least for the foreseeable future, a modicum of realism suggests that we must consider the range/value tradeoff for EV's in the context of conventional cars -- in particular of small, modest performance cars, such as EV's will be -- as an available alternative to prospective EV users.

In that context, how far must the range of an electric car be before the owner begins to consider its range limitation relatively unimportant? (Perhaps a more useful way of putting this question is, how long does the range have to be before buyers are willing to revise their expectations of how the car could be used?) The first issue one must face, it turns out, concerns how the notion of "range" is to be defined. For the "range" of an EV can easily vary by a factor of 3 using various commonly used technical definitions of range; and none of the commonly used definitions of range correspond to what a potential user is likely to think of as its range. A private buyer is likely to suppose that if the vehicle's range is given as 50 miles, then he will be able to use the vehicle with confidence on any day when he is confident he will travel no more than 50 miles. But if the buyer assumes that a vehicle which has been certified to have a 50-mile range over

the standard SAE metropolitan driving cycle¹ meets this criterion, then he is likely to be severely disappointed.

The basis of the problem is simple enough, although the solution is not so simple. For conventional cars, nominal driving cycles have been developed which are representative of typical conditions. The most widely used is the EPA's Federal Driving Cycle. Vehicle performance over this cycle provides an estimate of average fuel consumption and average emissions under typical urban driving conditions. These results will be highly non-representative of performance under unfavorable conditions, such as during a traffic jam. But the cycle is nevertheless very useful for its intended purpose, since one is ordinarily interested in average performance, not performance on any particular trip.

But fuel economy on a particular trip would be very important if conventional cars were restricted to very small fuel tanks which could not be readily refilled. The driver would have to worry about how far the car would go under the particular conditions that might be encountered. It would be small comfort to a driver who ran out of gasoline 5 miles from home on a 30-mile trip to know that the car, when new and tested under a standard set of conditions, ran for 50 miles. But this is almost exactly the problem that arises in specifying a nominal range for an electric vehicle. The standard cycle is calibrated to require approximately the same energy as the more complicated -- and more demanding in terms of speed and acceleration -- EPA driving cycle. A properly calibrated standard driving cycle is useful for estimating average energy consumption and for comparing one EV with another. But it may easily be drastically misleading as a mea-

¹Society of Automotive Engineers Electric Vehicle Test Procedure. [105]

sure of the practical range of the vehicle. Since this quite fundamental point is generally neglected, we will explore it in some detail in the following subsection.

7.4.2 Defining "Range"

What we would like to be able to specify would be the scales along the vertical and horizontal axes of Figure 7.1, and we would like to do so for various classes of users (private cars, urban delivery vehicles, buses, etc.). Data to do so do not exist: one can hardly give reliable estimates of consumer response to a product (a mass-market EV) which does not yet exist. Nevertheless, one can make some crude but useful approximations.

Reproduced below (Table 7.3) is one of the few sets of reasonably well documented data on actual (rather than calculated) EV performance. The vehicle here (the ESB Sundancer) was a test bed (i.e. not designed to production comfort, safety or economy standards) built to exhibit the maximum performance obtainable with lead/acid batteries as of 1971. [106] The lead/acid batteries were experimental units with considerably higher performance than those commercially available today (1975). The numbers, therefore, were and remain optimistic as an indicator of what might be obtained in a production car with current mass-producible lead/acid batteries, though perhaps conservative as an indicator of what might be obtained with lead/acid batteries 3 to 10 years from now. The reader will note that the reported ranges vary by a factor of 3, depending on how the measurement was made. Some insight into the causes of this large variation are given by Figure 7.2.

The figure shows the force (energy per unit distance travelled) required at the wheels (vertical axis, in logarithmic units) as a function of the speed. Two things to particularly note are the increase in force required to maintain

Table 7.3

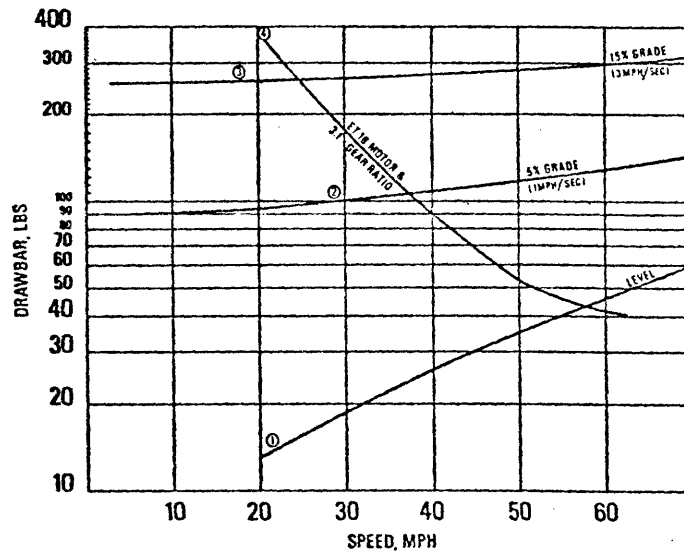
SUNDANCER RANGE FOR VARIOUS TESTS^{1,2}

<u>Test</u>	<u>Range (miles)</u>
30 mph steady speed	140-150
60 mph steady speed	60-65
SAE residential driving cycle	75-80
SAE metropolitan driving cycle	50-55

¹Source: [106].

²Experimental battery.

Figure 7.2



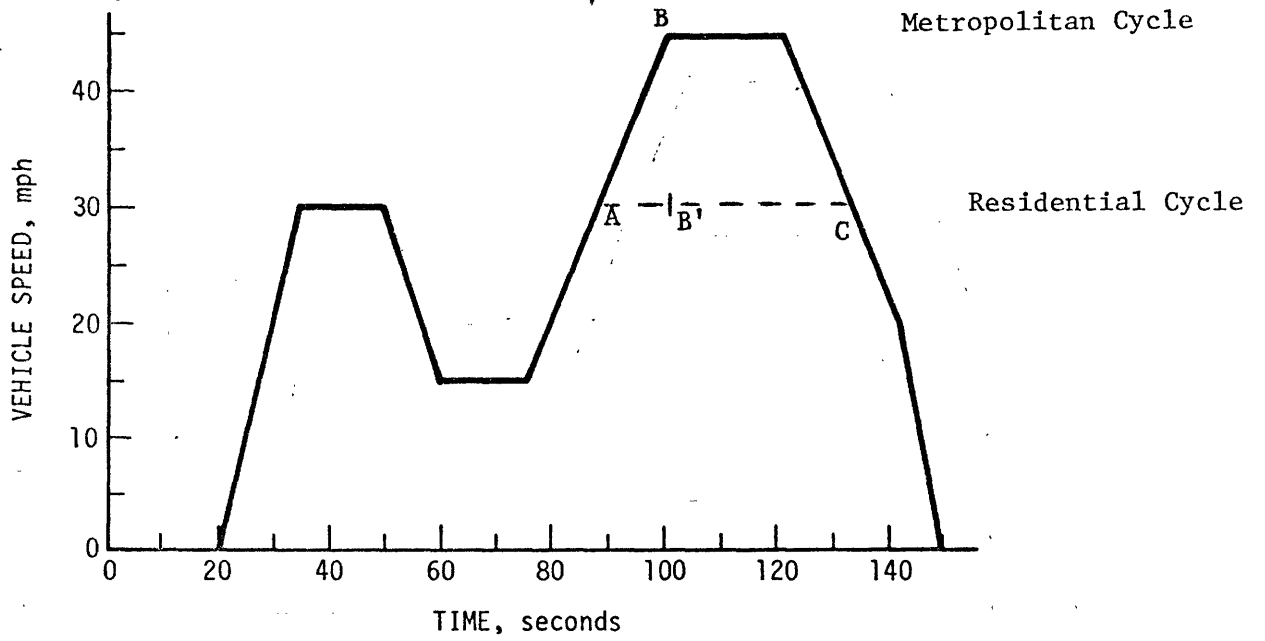
ESTIMATE ROAD LOADS FOR SUNDANCER ELECTRIC
Vehicle [106]

a steady speed as the speed increases, and the much greater requirements of acceleration or hill climbing. The first is largely due to the increased aerodynamic resistance as speed increases, and leads to an increase in total force greater, although not very much greater, than the proportionate increase in speed. (Here a tripling of speed from 20 to 60 mph leads to something less than a four-fold increase in required force; a doubling of speed from 30 mph to 60 mph leads to somewhat more than a doubling of required force.)

If we now look back at the Sundancer performance data (Table 7.3) we see that, as should be expected, the steady-speed range at 30 mph is more than double that at 60 mph. The drop in range shown in Table 7.3 is somewhat greater than the drop in force shown in Figure 7.2. This is because, as noted in Section 7.2, the faster energy is drawn from a battery, the lower will be the total amount of energy the battery can deliver. Consequently, increasing the power required -- the product of the force and the velocity -- cuts the total energy available. This effect is not too important for changes in velocity: you have to read the chart carefully to see there is a discrepancy. But when we consider the effects of acceleration -- or, equivalently, hill climbing, which also requires energy to overcome gravitational inertia -- the tradeoff of power for total energy becomes very important.

Looking at Figure 7.2, one can note that the power required for accelerations ordinarily encountered in urban driving -- keeping up with the normal flow of traffic requires accelerations of about 3 mph/sec. -- is much higher than the power required for steady-speed driving, even at highway speeds. Consequently (in addition to the greater energy dissipated in

Figure 7.3



Electric Vehicle Driving Cycles [105]

braking for stops) the battery is forced to perform at points along its discharge curve where severe tradeoffs are encountered between power and total energy. The sharpness of this effect will depend on how far within its maximum capabilities the battery is operating. The strong effect of a rather modest incremental acceleration imposed on the Sundancer warns us that an EV equipped with lead/acid batteries, barring really striking advances in that technology, will be vulnerable indeed to degradations of nominal range in the event of unanticipated demands for power. On the other hand, it is conceivable that advanced batteries may provide sufficient power densities so that the pronounced total energy penalties at high power apparent in the Sundancer data can be ameliorated (though not eliminated). But whether this favorable development will come about remains to be seen.¹

The significance of this power/energy tradeoff can be illustrated by superimposing the SAE metropolitan driving cycle over the SAE residential cycle. Sundancer was able to achieve only 2/3 of the residential cycle range on the metropolitan cycle. Yet the difference in power required over this 150-second cycle (repeated many times in a single range test) is important only in the 12.5-second interval between points A and B. (The energy required between points B and C is not very much larger for the metropolitan cycle, since about half the time the vehicle is drawing no power as it allows the speed to drop.) Further the accelerations involved are modest: only 1.2 mph/sec.

¹Most published power/energy diagrams inadvertently, but misleadingly, show little or no negative slope in the curves for advanced batteries. This reflected the limited knowledge available until recently on performance of advanced batteries. Now that measurements are becoming available on the performance of experimental cells, it is clear that the effects are significant. How significant the effects will be cannot be known with confidence until later in the development programs.

Consequently, we can expect that EV ranges may diverge sharply from their values for average conditions, being especially sensitive to variations in the acceleration profile of a particular trip (number of stop signs or lights encountered, hills, smooth flowing or congested traffic, etc.) Even on familiar trips (to and from work, for example) these factors will vary from day to day. Much more severe problems will arise if the vehicle is not restricted to trips where the driver can be assumed to know fairly accurately just what distances and conditions will be involved.

Indeed, we encounter two sources of difficulty in extrapolating from the generally used nominal ranges of electric vehicles (defining nominal range as range estimated on the basis of the SAE J227 driving cycle): First, the cycle itself does not represent actual driving conditions: in particular the accelerations required are less than those which are ordinarily encountered. One would expect, consequently, that actual average EV ranges would fall short of the nominal range. However, the GRC study [101] reports that a comparison of calculated range over the EV cycle compared to the EPA urban cycle (the latter derived from actual driving experience in Los Angeles) shows little discrepancy. We find this puzzling, but we cannot flatly assert an error has been made.

However, on the second point, there is no ambiguity. Results obtained under the SAE J227 range test represent, at best, average performance, typically reported for performance with a new battery. By the very definition of "average", this nominal range must be greater than the range a driver can feel confident of obtaining.

To these difficulties in interpreting EV ranges must be added a considerable number of others. As already noted, battery performance degrades with

use. Normal practice today with lead/acid traction batteries is to regard the battery as worn out when it has dropped to 60% of its original performance. If this procedure is followed, then an EV with 50 miles nominal range will have only 30 miles nominal range when close to battery replacement time. Cold weather increases road load; as do winds, underinflated tires, wet roads and various other factors. Without choosing extreme conditions, these factors can accumulate to an increase in road load of a factor of 2. Driving in snow would be a severe problem.

Another kind of problem occurs if the battery itself is allowed to become cold, as every driver knows from cold weather problems with starter batteries. The cold weather effect noted before is primarily due to the effect on tire friction. Under normal conditions, the cold weather effect directly on the battery may be minor, since the internal temperature of a large traction battery would not fall rapidly. But if for any reason, a lead/acid car were left parked on the street overnight on a severe winter night, the range might be short indeed on the following day.

Driver performance will, of course, affect ranges considerably, given the sensitivity noted to acceleration. A driver who seeks to conserve energy by accelerating slowly from stops, coasting to stops, and keeping speed down (especially on hills) will obtain substantially longer range than a more typical driver. Unfortunately, such practices might also make this energy-conserving driver a considerable annoyance to others, and indeed a safety hazard. Such problems may arise whether the driver is trying to conserve energy or not, since performance degrades (on a given day) as the battery is depleted. This effect is not important under the SAE J227 cycle, since the acceleration demanded by the cycle never exceeds 2.14 mph/sec.

But in actual use, it is important to be aware that a vehicle designed to be able to meet reasonable minimum performance requirements on a fully charged battery (say 3 mph/sec. acceleration from 0 to 30 mph) in fact will not be capable of doing so over a substantial fraction of its nominal range, so long as the SAE J227 cycle remains the basis for range tests.

A final point worth noting is that the SAE J227 cycle (as may be seen in Figure 7.2 of the text) includes a 20 second stop before each 130-second cycle of driving. In the EPA cycle from which the electric vehicle cycle is derived an equivalent amount of standing time is included, since otherwise fuel consumption and emissions during engine idling is erroneously neglected. For an electric car, the effect of including standing periods in the cycle is the opposite of the effect with a conventional car. During standing periods, no energy is consumed; rather the battery has a chance to regenerate some energy. It is proper to include this effect in obtaining average range numbers; but of course in actual driving, the total amount and distribution of standing time will vary widely, and there will be occasions on which it is essentially absent.

Obviously it would be useful to make at least a modest effort to gather data which would permit a more quantitative treatment of the problem of defining practical range of electric vehicles than is possible here. A significant amount of data has been accumulated through British experience with electric milk delivery vans and Japanese experiments with a small electric commuter car. We were not able to obtain this data in time for the present study, but presumably it is available. A systematic collection of data in this country could be undertaken at modest cost in connection with the USPS experiments with electric postal delivery vans. Finally, an analysis of the

raw data on which the EPA cycle -- and hence, indirectly, the electric vehicle cycle -- was based would provide insight into the distribution of driving conditions which are represented by the standard cycles, and into the extent to which the EPA cycle provides an appropriate basis for EV range calculations. One could then compute a distribution of estimated range for a given EV, which would be far more useful than the single number which can be obtained now.

To sum up, then, we can note that:

1. The steady-speed (on a flat road, no wind) range of an electric vehicle, to a first approximation, can be taken as inversely proportional to the speed. The approximation increasingly overestimates range as speeds rise.
2. A well-designed standardized driving cycle can give a good approximation of average range in actual driving, and further is quite appropriate (and, in fact, necessary) as a basis for comparing alternative electric vehicles. But it seems likely to us that the SAE J227 cycle overestimates average range.
3. In any event, the standardized test will be a poor indicator of actual ranges obtained on a given day (since precipitation, winds, and temperature all have substantial effects on energy requirements) on a given trip (depending on how often hills, stop lights, merging or passing situations are encountered) with a particular driver (fast or slow) in a particular car (old batteries or new).

In summary, 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. Indeed, 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 combination of not extreme conditions under which the car will obtain an actual range only 20% of nominal.

For example, suppose that the battery has been depleted to 70% of its as-new capacity; nominal 50 mile range is now cut to a nominal 35-mile range.¹ Suppose further that the day is moderately cold (30° F), tires are slightly underinflated and there are wet roads creating bad driving conditions and a moderate headwind of 15mph. From tests in [106] the car would have a range of about 17 miles under these conditions, provided that all other conditions were equivalent to those of the SAE J227 cycle. However, during roughly the last third of this trip, while the vehicle keeps up with the SAE J227 cycle, it would not accelerate at the 3 mph/sec. ordinarily encountered in leaving a stop light, much less the 4 mph/sec. typical of merging onto a freeway. So if the driver is nervous or uncomfortable in a vehicle that cannot keep up with the normal flow of traffic, he will find himself unhappy after about 12 miles. Finally, unless the driver is taking a trip he regularly takes, and for which he has noted the mileage, he is hardly likely to be confident that what he supposed is about a 10-mile trip will not turn out to be 12 or even more miles.

Of course, importance of these factors vary from driver to driver. An owner could replace the battery sooner than its nominal life, but only at a substantial incremental expense. Some owners would regard the risk of having to creep home under unfavorable conditions as of almost no concern (so long as they could get home); others will be very uncomfortable at the thought of this prospect. Obviously the problems will be far less severe in parts of the country which have few hills and a mild, dry climate. But even in the

¹Batteries are typically replaced when depleted to 60% of original performance.

most favorable context, it is clear that a 50-mile nominal range cannot be taken as a 50-mile practical range; and in unfavorable situations, our illustrative 20% of nominal may in fact be an entirely realistic estimate of the practical range of the vehicle as perceived by the driver. On the other hand, for a specialized vehicle (not a mass market passenger car) with a well-defined and favorable duty cycle under conditions which vary little from day to day, the nominal range on the SAE cycle may understate its practical capabilities.

In the face of these difficulties, then, can we say anything useful about the likely shape of the range/value curves illustrated in Figure 7.1? In fact, a number of useful inferences can be drawn.

7.4.3 Discussion of Range-Value Plots

We have tried to show why the problem of defining the range of an electric vehicle is a subtle one. But within the present effort we could not carry out the kind of detailed data-gathering and analysis (previously discussed) that would quantitatively define EV range in a more relevant way than the widely used nominal ranges based on the SAE test procedure.

Further, the discussion so far has concerned the variability of range primarily as a function of the variability of the conditions encountered in driving a car. That is, we have considered mainly the physical aspects of EV range. Equally important, though, are the psychological aspects. There are people who begin to be concerned about the possibility of running out of gas as soon as their fuel gauge falls below the half-full mark; there are others who rarely bother to re-fuel until the gauge is on empty, feeling quite secure in the knowledge that there is a gallon or so in reserve even

when the gauge (first) reaches the empty mark. Analogously, the practical range of a given EV will depend on the perception of the user, not simply on the physical properties of the car. However, for the purposes of the present discussion, we may take the practical range of an EV as half the nominal range based on the SAE range test.

The initial role of a mass-market electric passenger car is commonly, and reasonably, taken to be that of a second car for urban use. In that role, it is often assumed that a range of about 50 miles would be satisfactory. [101,107] The argument runs as follows: a typical car is driven about 10,000 miles per year, or an average of under 30 miles per day. A family which owned both an EV with 50-mile range and a conventional car with unlimited range would be clearly inconvenienced only on occasions when both cars were needed for more than 50 miles travel. If one makes some simplifying assumptions about the skimpy available data (assuming independence, log-normal distributions of trip length, etc.), one finds that a 50-mile range would be adequate for an urban second car on more than 95% of days. The recent Committee Report for the Electric Vehicle Research, Development and Demonstration Act of 1975 puts that number at 98%. [108].

The assumptions on which 50-mile adequate range must be based (in addition to the statistical assumptions noted above) include 1.) that the household knows at the start of the day how far each driver -- or at least the driver of the EV -- will travel; 2.) that the household perceives no substantial inconvenience in trading off cars among its members; and, perhaps more important, 3.) that high theoretical availability is an accurate measure. For it seems very possible that only when the vehicle has a reserve energy storage capacity considerably beyond what the owner ordinarily needs

that he can feel reasonably secure about such things as forgetting to plug in the car at night, or a blown fuse during recharge, or a teenager trying to drive the car faster (and harder) than he should.

Overall, in terms of a range-value curve, it seems reasonable to consider the 50-mile range as reaching the shoulder of the curve for the typical driver; but it is not reasonable to assume that because one has defined an adequate urban car as a car with 50-mile range, that owners will therefore put out of mind the fact that if they choose to own such a car they must accept the reality that the car will not always be able to take them where they want to go, even if they have another car for long trips. With a 50-mile range, there will be days when there are extra errands to run, or an unexpected trip to make, or particularly severe driving conditions, when the car is inadequate.

Again in terms of a range/value curve, we want to consider the likely range at which the range limitation of the vehicle becomes a minor factor, so that we may expect that substantial numbers of typical users might find an equal-cost electric car a completely satisfactory or even preferable substitute for a conventional car (considering such likely advantages of advanced electric cars as low maintenance, extremely quiet operation, exceptionally smooth acceleration). Essentially, what we wish to estimate is a range that is sufficiently long so that a driver need not be conscious of any range limitation in normal usage, and (even better) long enough so that it is possible to use the vehicle on occasional out-of-town trips.

A nominal range of 200 miles may be more than enough to meet this criterion. The range is now long enough -- very possibly, though not assuredly, longer than necessary -- so that even considering the manifold problems

discussed earlier, we can reasonably assume that the inconvenience of the range limitation for routine travel is reduced to the level of the problems comparable to the possibility that a conventional car may have mechanical difficulties. Further, the range is long enough so that some out-of-town travel can be managed. The potential owner need not think of himself as choosing a vehicle which forecloses the possibility of such travel.

To what extent this would prove to be the case depends substantially on the kind of supporting infrastructure that might develop in the event substantial numbers of such vehicles came into use. The practical range for out-of-town travel of a 200-mile nominal range vehicle may not be much more than 100 miles. This is partly because the improved range at a steady highway speed shown in Table 7.3 overstates the actual prospects, since actual highway driving involves a good deal of acceleration and grade-climbing, creating periods of very high power demand since power is the product of the force required times the speed at which the vehicle is travelling. And the concerns that the possibility of running low on power creates, like the problems of mechanical failure in a conventional car, are more worrisome in out-of-town travel. Hence the owner's judgement of what he considers practical range will be more severe than for travel which is never very far from home. On the other hand, should a substantial number of such vehicles be in use, one could expect specialized services to evolve which ease the problem of the long-distance EV driver: we could expect to see facilities for obtaining at least a partial recharge during breaks in the trip, and we could expect to see arrangements for rental of generator-trailers which could supplement the energy available from the car's own batteries.¹

¹Such trailers are currently used in Britain to extend the range of electric milk delivery vans on long runs.

In short, then, we reach the rough and tentative estimates that an electric passenger car capable of substantial market penetration would probably require a nominal range of 100 to 200 miles (practical range of 50 to 100 miles), with the lower number estimating the capability of a vehicle which would be a reasonably satisfactory substitute for a conventional car in urban use, and the higher number representing a vehicle that might be judged to be quite competitive with a conventional car for many buyers if both were available at comparable cost.

We stress again that over the long run any such numbers are contingent on what one assumes about public policy and the availability of gasoline or other liquid fuels. If one were to assume severe rationing of gasoline, electric cars of very low performance indeed might find a market, as would greatly increased use of busses, motorcycles, etc. If, as is perhaps equally likely, gasoline prices (in constant dollars) remain about the same as they are today over the next 20 years, with no severe rationing or frequent shortages, and absent substantial subsidies for EV's, then it is hard indeed to see a significant private car market for a 100-mile range vehicle. A useful way to think of the 100-mile nominal range is as a reasonable estimate of the minimal nominal range at which it is likely to be politically feasible to stimulate a substantial shift to electric vehicles, should that be judged appropriate public policy: the EV is not yet quite competitive with a conventional car; but the inconvenience imposed on the user (i.e. on voters) is nevertheless not very severe. It is really only with vehicles significantly beyond this hypothesized 100-mile "shoulder of the curve" that it is plausible to envision a significant impact of electric cars in the absence of rather strong pressures imposed by government policy.

7.4.4 Implications for Marketable Vehicles

We have seen that a car with a nominal range of 50 miles is by no means adequate if our criterion is a 50-mile practical range. For the practical range could hardly be taken as more than 25 miles, which is less even than the average day's travel. In parts of the country with severe winters or hilly terrain, the guaranteed range would be substantially less. Since with current technology (i.e., lead/acid batteries) an electric car with performance approaching that of a conventional subcompact could hardly be provided with a nominal range of significantly more than 50 miles, we must judge that such cars would be very inconvenient for a typical user. In terms of a range/value curve, their value, for a typical user, would be modest compared to a conventional car, since a good used conventional car is very likely to be preferred to an electric car of such limited range.

It does not seem to help matters to consider the low-mileage driver as a particularly promising EV market. About 25% of cars are driven under about 6,000 miles per year, or an average of only 16 miles per day [73]. At least in favorable parts of the country (mild climate, flat terrain) this presumably falls within the practical range of lead/acid cars. However, under these specially favorable conditions, two problems arise. First, for some substantial fraction of low-mileage users, low average mileage carries no implication that the vehicle is used only for short range travel. For example consider the owner who belongs to a car pool or lives close to work, and uses the car primarily on weekends. His average mileage per day over the year is low, but his average mileage on the days when he actually accumulates most of the mileage on the car is not low. Second, even if the average mileage per day is not a misleading indicator, an economic problem arises. This is partly be-

cause battery life tends to be partly a function of the number of charge/discharge cycles (not simply a function of the total mileage) and partly because unless the car is heavily used, the owner cannot obtain the economic advantages associated with the long operating life and low maintenance of electrical equipment.

We encounter a fundamental dilemma: unless the car is driven as much as a typical conventional car, its cost per mile will be substantially higher than that indicated by calculations which assume the canonical 10,000 miles per year. On the other hand, if it is driven 10,000 miles or so per year (and perhaps even if it is not) then the kinds of ranges that seem plausible for lead/acid cars will make range limitation a recurring inconvenience to the driver. Either way there is a gross mismatch between the costs of the vehicle and its value compared to that of a conventional alternative.

This does not mean that no electric cars will be marketed within the next few years. In a rich country of 200 million people, there is some market for electric cars which can be built today, as there is some market for \$50,000 luxury cars and for antique Model T's. But the prospect of a nationally significant market for such cars is negligible.

It is physically possible to build an electric car today with performance considerably exceeding lead/acid performance, possibly reaching an "almost competitive" range. Various batteries, such as silver-zinc and nickel-cadmium, are commercially available which would allow EV performance to be roughly doubled compared to lead-acid cars. But the costs would be extravagant. The cost of the silver/zinc battery powering the GM Electrovair experimental vehicle was reported as \$15,000 (1964 dollars). Even though a major fraction of the cost could be reclaimed through salvage, the sheer carrying costs of

the investment required and the problem of physical security for the material present irremediable difficulties. Nickel/cadmium batteries are 3 to 6 times as expensive per watt hour as lead/acid.

This does not quite settle the issue of near-term prospects of EV's; for one can make a case for subsidizing electric vehicles. The argument for subsidies turns partly on the grounds that the social value of conserving fuel exceeds the price charged to individual drivers. Hence EV users could very reasonably be subsidized at least to the extent of the difference between the market price of fuel and the "shadow price" (somehow chosen) reflecting the full social value of the fuel saved. An additional increment (again, somehow chosen) could be allowed for the social benefits that are estimated to go with reduced vehicle emissions.

A second line of argument for subsidies concerns the social value of stimulating an electric vehicle industry. If we believe that it may be important to the nation to have the option to move expeditiously to widespread use of electric cars late in this century (when incentives for fuel conservation may be far more intense than today, and when superior battery technology may be available), then it would appear advantageous to stimulate the evolution of an electric vehicle industry. For the more gradual the transition to substantial EV usage, the more manageable will be the transition, involving (as it would) major changes in a vastly important component of our social system, affecting the interests and (perhaps as important) the habits of almost every part of society. Further, a growing EV industry would stimulate a broad advance in technology and know-how applicable to electric vehicles, no element of which is comparable in importance to improving battery technology, but which (in sum) adds up to an important element of the ulti-

mate feasibility of wide EV usage.

We cannot address these matters in detail within the present discussion. But by considering the prospects of current and near-term technologies, one can get some sense of the plausibility of effectively stimulating the industry with subsidies that could be reasonably justified. We believe this is sufficient to reach some clear judgements about the kind of program to stimulate EV usage which would be most attractive, if such an effort is undertaken.

In this context of near-term prospects, we want to consider the possibility of improvements in nickel/zinc technology, which has attracted a good deal of interest in the past year or so. [109,110] This technology could provide (assuming current R & D efforts are successful) an electric car with nominal range in the 100 to 200 mile category we have designated as "almost competitive". From the estimates of Table 7.1 we can see that their cost would be comparable to lead/acid cars, but their range would be more attractive. (The Table 7.1 nickel/zinc entry is based on GRC's estimate of the cost of a vehicle with 150-mile nominal range.) Thus, in contrast to current (and generally forecast) lead/acid technology, the vehicle could plausibly be "almost competitive"; while in contrast to silver/zinc or nickel/cadmium technology the costs may not be absolutely forbidding.¹

The way we will proceed will be to develop a necessarily crude but we

¹Since the nominal range of the nickel/zinc car on which the Table 7.2 number is based was about 150 miles, one might consider the cost per mile number conservative, since the batteries are large enough to provide substantially more than the minimum nominal range we judged reasonable. However, whether this proves the case depends on the power/energy tradeoffs for the nickel/zinc batteries. On the sketchy information presently available from informal discussions with developers, it seems quite possible that a nickel/zinc vehicle with adequate power may necessarily have something of the order of 150-mile nominal range on the rather benign SAE cycle.

believe reasonable notion of how much battery technology must improve to provide a car in our "almost competitive" range, assuming what seems a conservative (high) estimate of the price of conventional fuel. The latter may be interpreted either as an actual price in the event of a further large increase in the cost of crude oil (or substitutes); or as a shadow price for fuel, with the difference between the actual price and the socially-valued shadow price used to subsidize electric vehicles.

Of course a vehicle at the lower end of our "almost competitive" range (i.e. 100-mile nominal range) would still require subsidies (even in the event of high fuel prices) for substantial market penetration to make up for the difference in the value to the user between this car and an unlimited range conventional car. Consequently, the analysis leaves what we should judge to be a generous margin for subsidies (or increments to fuel-related subsidies) intended to take account of the social value of reduced emissions and stimulation of the industry.

We also consider the prospects of EV's in commercial fleet applications (rather than in the role of private cars) and, briefly, the possibility of hybrid vehicles.

Against this background, we then reach the essential questions of the present study: the problems and prospects of Federally-supported R & D on EV technology.

7.4.5 Technology Improvement for an "Almost Competitive" Car

Suppose that gasoline prices (or equivalent prices for some substitute fuel for heat engines) should reach \$1.20 per gallon.¹ This corresponds to

¹Or, equivalently, assume that the social value (shadow price) of gas is treated as \$1.20, with the EV subsidized to the extent of the difference between price at the pump and \$1.20.

a price of crude oil of around \$30/barrel, or triple current prices. Numerous other possibilities (syncrude, methanol from wastes, shale oil, even methane from wood) become very plausible options at such extreme prices.

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. One would like to have some feel for how much improvement over current technology is required in order to make a significant impact of electric cars plausible: we have examined that issue in terms of capability (in particular, the range) which is likely to be required. We now consider the cost side of the picture.

It is clearly possible to produce small conventional cars that will deliver 30 miles to the gallon in urban driving: indeed cars approximating this fuel economy are already on the market, and further improvements are universally anticipated¹ (see Chapter 4). Thus the cost per mile of fuel for cars comparable to foreseeable electric passenger cars is unlikely to exceed 4 cents per mile so long as the price of crude oil or substitute equivalents does not exceed \$30/barrel. Electric vehicles today invariably cost (purchase cost) substantially more (exclusive of the battery) than comparable conventional vehicles. However, assuming that through economics of mass production and technological advances, and taking account of the low maintenance and long life

¹The Honda Civic obtained 29 mpg on the EPA city/suburban cycle; 40 mpg on the highway cycle.

of electric motors, these lifetime costs per mile became comparable.¹ Assume the electricity usage is 0.5 kwh/mile (taking into account charging and subsequent losses) and that, optimistically, off-peak power is available at 2¢/kwh. Hence electricity cost is about 1¢/mile, and therefore 3¢/mile is available for battery depreciation if the electric vehicle is to be equal in cost to the conventional vehicle.

How high would this cost be for an "almost competitive" car with current technology? There are serious problems in estimating this number even for current technology, since no lead/acid car currently on the market even approaches our "almost competitive" requirements. (Consumer Reports has recently provided an appraisal of currently available EV's [103]; some reasons for the difficulty of estimating costs of batteries are given in Section 7.5.1 below.) GRC's estimate of "worst performance" for a future lead/acid battery might be taken as a reasonable estimate of today's state-of-the-art. If so, the cost comes to about 10¢/mile [101, Task Report 9, Table 2.3], but this is based on 1967 information. We are not aware of any claims for major advances since that time, so that an estimate for current (1975) technology of 6¢/mile seems optimistic. This is still a factor of 2 higher than needed to make a lead/acid car equivalent in cost to a conventional car.

Consequently, in addition to the factor of 2 improvement of performance beyond the best current batteries (increasing nominal range from 50 miles to

¹One must distinguish here between the electric passenger car, and the electric commercial vehicle. Total cost per mile comparability is clearly more than feasible with commercial vehicles, where their intensive use makes maintenance a more important component of cost than for a private car, and where vehicles are used long enough to take full advantage of the long useful life of an electric motor. The assumption of the text is reasonable, though not conservative, for a private passenger car. The assumption of the text on the cost of off-peak electricity is decidedly optimistic.

our "shoulder of the curve" estimate of 100 miles), an improvement in costs by at least a factor of 2 is also required. In terms of a measure of overall performance per dollar we therefore require something of a factor of 4 improvement over current battery technology to build electric passenger cars that begin to be plausibly significant in terms of petroleum conservation. This is the number to have in mind in considering potential payoffs from efforts to develop a potentially viable electric car option. Beyond this minimum required step in battery technology, one would like to see at least a significant potential for the technology pursued to eventually reach a further factor of 2 improvement in performance in order to reach vehicles which might plausibly be able to compete with conventional cars in the absence of the kind of palpable crisis that would create (or make politically plausible) the severe constraints on fuel availability that would be required to make substantial market penetration possible for our hypothesized "shoulder of the curve", 100-mile nominal range, vehicle.

7.4.6 Fleet Operations

Note that this discussion has been concerned solely with the electric passenger car. For the reasons such as those reviewed, the passenger car is the most difficult role for the electric vehicle. Selected fleet operations of electric vehicles are substantially less demanding. They are likely to be important in the evolution of an electric vehicle industry, even though fleet operations alone are not likely to add up to a nationally significant impact on fuel conservation.

It will be useful to review some of the reasons why fleet operations are far more advantageous for electric vehicles.

1. Maximum required daily ranges for a number of applications are reasonably short and highly predictable. (The current U.S. Postal Service experiment with electric mail delivery trucks will require only 11 miles per day on an average route. [111] The day-to-day variation in range on a given delivery route is essentially zero.)

2. The fleet manager can assign vehicles (or batteries to vehicles) to make the best use of his inventory. The problem of loss of battery performance with age is a minor one in an operation where it merely requires assigning vehicles with older batteries to less demanding routes, rather than continual adjustment of the driver to lower performance as the battery ages.

3. Battery exchange, maintenance, and recharging are all simplified when vehicles are routinely returned to a central base.

4. Vehicle failure is not a significant problem for the driver. Not only are such failures less likely than for a passenger car, given the predictability of routes and the central maintenance and charging facility, but the consequences of a failure are entirely different for a fleet operation and a private driver. For the former, battery exhaustion on 1% of trips would be a minor cost in the overall operation, and handled by routine procedure. For a private driver a 1% failure rate would be intolerable: few people indeed would tolerate a vehicle which had to be towed home 3 days a year (especially a vehicle which has (at best) minimal cost advantages over a conventional vehicle and which is burdened with the performance disadvantage of limited range).

5. For typical fleet operations, the total usage per vehicle generally exceeds that of a private passenger car. This advantage bears significantly

on the relative cost of electric as compared to conventional vehicles in at least two ways:

a.) Other things equal, a battery designed to provide modest performance over a long duty cycle (such as an urban delivery vehicle) will produce markedly better overall output (measured, say in ton-miles/\$) than a vehicle which must deliver its output in a brief period (a passenger car which is likely to be in actual use less than 2 hours a day).

b.) A significant prospective advantage of electric vehicles is low maintenance costs and long life relative to a conventional vehicle. The more intensively the vehicle is used, the more significant this advantage becomes.

6. The vehicle can be tailored to meet the particular requirement of the fleet. (The U.S. Postal Service electric vans would be almost useless in any other operations other than delivering mail. But since their only mission is delivering mail, they can be optimized for precisely that specialized role. Similarly, regenerative breaking -- recapturing a portion of the energy used to accelerate the vehicle -- is only marginally interesting for a passenger car. But an urban bus, which dissipates a large fraction of its total energy in braking, might profitably incorporate this feature.)

7. Finally, it is in specialized fleet applications that relatively small numbers of electric vehicles are most likely to yield relatively significant environmental gains. Spread widely a small EV fleet will be inconsequential. But concentrated in particular areas, such as urban centers, the environmental effects may be important. Indeed, such environmental ad-

vantages have played a significant role in the existing limited commercial market for electric vehicles: an important asset of electric golf carts is that they are quieter than gasoline equivalents; similar considerations have helped the promotion of electric power for lift trucks and in-plant personnel carriers. EV's for use in urban centers with dense traffic will have the greatest efficiency advantage as compared to conventional cars, since no energy is used idling.

In sum then, there are many reasons to suppose that successful early applications of EV technology will come in the field of specialized fleet operations, not in the field of private passenger cars.

One possibly important qualification to this discussion is required. We have considered only "pure" electric vehicles. Numerous possible hybrid vehicles have been explored in paper studies, (and occasionally, though to date not very successfully, in test vehicles). Hybrids generally, though not always, involve electric cars as one of the components. A hybrid EV may have sufficient power from the non-electric component of the drive to allow the vehicle to get home even in the event of battery depletion. Such on board "insurance" is likely to be very important to the driver of a passenger car, even if it is very rarely needed; for the burden of worrying about whether the car will be adequate is probably more important in limiting the acceptability of short-range vehicles than the perhaps rare occasions in which serious difficulties actually arise.

Thus, in principle, a hybrid approach to the electric passenger car has the prospect of producing a competitive vehicle with considerably more modest improvement in battery technology than appear to be necessary for a pure electric vehicle. The question is whether the economics of such an approach

could be made plausible. Further, a hybrid approach is probably only interesting if the development is one that provides growth potential to evolve into a pure electric vehicle. And, finally, many of the arguments just given for expecting early EV applications to be most feasible in connection with commercial fleets, not private cars, apply as well to hybrids.

On net, there are strong grounds for skepticism about hybrid passenger cars. But the issues have not been explored in this study, and warrant further study.

7.5 R & D Issues

7.5.1 Some Pitfalls in Discussing Battery Technology

A source of difficulty in making judgements on battery R & D prospects is that the problem of defining the capabilities of a battery is as beset with pitfalls as the problem of defining the practical range of an EV (to which so much space was devoted in the previous section). It is useful to list some of the major design considerations in a battery:

1. Power density (determining the weight of a battery adequate to provide required performance).
2. Energy density (determining the weight of a battery adequate to provide given range under some standardized set of conditions).
3. Manufacturing cost (considering both inherent cost of materials, and suitability of the design to mass production).

4. Cycle life (i.e. the number of charge/discharge cycles before the battery must be replaced).

The often severe tradeoffs among these design features (we have already stressed the power/energy density tradeoffs) are easily lost sight of in discussions of battery improvements. For example the performance of current lead/acid batteries is well below 20% of theoretical maximum performance. Consequently, it is not surprising to find there is no severe problem in building an experimental battery which markedly outperforms existing commercial batteries. Where severe problems tend to be encountered is in obtaining the markedly improved performance without substantially offsetting disadvantages in areas such as manufacturing costs or cycle life.

Other areas where misunderstandings can easily arise include the following:

1. Discharge time. (We noted in the previous section that a battery designed to be discharged over a fairly long duty cycle -- say the 6 hours of a postal van, or the 8 hours of a lift truck -- will give better performance than a car battery which must be designed to discharge in an hour or two.)

2. Degradation during a single cycle. (Again, as noted earlier, battery performance in terms of maximum power output degrades not only over the life of the battery, but within each cycle as the battery is discharged. The battery size required to maintain some minimum performance level throughout a nominal "deep discharge" will be quite sensitive to the extent of this degradation.)

3. Degradation across cycles. (The "cycle life" mentioned earlier is generally taken to be the life of the battery until performance has fallen to 60% of the original level. A battery which maintains a fairly constant

performance level almost to the end of its useful life, with severe degradation setting in only at that point, would obviously be superior to a battery which degrades rapidly at the beginning of its life, so that the new battery performance is drastically misleading as an indicator of typical performance.

4. Depth of discharge and cycle life. (The most favorable situation is likely to be that the effect on battery life of a given day's use is simply proportional to the fraction of a nominal deep discharge cycle which is expended. More typical, though, is that shallow discharges cause a more than proportional aging of the battery: that is, typically 10 days of use at 10% of nominal capacity wears the battery considerably more than 1 day of maximum use. Different batteries may vary sharply in this regard.)

The point of this brief review is to emphasize the extent to which any simple specification of battery R & D goals may be drastically misleading as an indicator of long-run performance and cost of a vehicle powered by the nominal battery. Further, many additional matters arise beyond those already mentioned: such as insulation and packaging for advanced batteries using molten electrolytes or electrodes, temperature controls generally, ease of integration of the battery into the vehicle when safety and maintenance considerations are considered, and so on.

An important inference which follows from this discussion is that one must be pessimistic about advanced technologies which appear to have only marginal prospects of meeting more than minimal performance goals. For even if explicit R & D goals are met, one must expect performance of production batteries to fall significantly short of performance calculated from experi-

mental devices once all of the tradeoffs that have to be faced in an actual operating vehicle have been dealt with.

7.5.2 Near-Term Battery Prospects

The problems just discussed create particular skepticism about the prospects for pure electric vehicles powered by lead/acid batteries to ever reach the "shoulder of the curve" performance and cost requirements suggested in the previous section, even though such performance is certainly theoretically within reach of the technology. Lead/acid batteries reflect a "mature" technology with a large and competitive existing commercial market. For many years there has been an incentive to private developers (here and abroad) to find ways to make batteries more cheaply, with higher performance, and longer cycle lives. It would be quite surprising if the kind of radical improvement in this technology that would be required for a reasonably acceptable passenger car were now to emerge. It is also worth noting that until fairly recent years, lead/acid batteries were critical in the performance of military submarines, because until the advent of atomic power, underwater performance was severely limited by battery technology. Thus the current state of lead/acid technology includes the results of a period of some decades -- approximately 1915-1955 -- during which promising improvements in the technology would have been strong competitors for naval R & D support in a number of leading technical nations, notably Germany, Japan, and later the Soviet Union.

To a lesser degree, the preceding point also applies to nickel/zinc batteries. However, one can be somewhat less pessimistic about the prospects here. Both Gould and General Motors have recently asserted that major improvements in the economics of these batteries are in sight. [109,110] Little

use has been made of this technology in the past, since the cost of nickel electrodes and the limited durability of zinc electrodes have combined to make the combination economically unattractive. (For some years performance has been sufficient to plausibly reach our "shoulder of the curve" requirements.) It is fair to report that there is a good deal of skepticism in other quarters of the industry about prospects here. These largely stem from the fact that a good deal of work has been done on nickel and zinc systems: nickel/cadmium and silver/zinc batteries have both enjoyed considerable support for highly specialized (generally military) applications, where their high materials costs have been acceptable. There is skepticism that a number of the major problems with the nickel/cadmium and silver/zinc batteries can be overcome to allow production of economically viable nickel/zinc batteries. It will probably be another two years before we have clear evidence of how well these R & D efforts are succeeding. No immediate issue of government-supported R & D appears to rise in this area, since the private developers assert they are adequately funded and are not requesting government support.

(This points to a more general problem with near-term technology, especially technology which is useful for a wider class of applications than EV's. If private firms are enthusiastic about the progress they are making, they tend to be reluctant to accept government funding: they do not want to compromise their patent position. It is when the venture looks too risky for private investment that managers permit their laboratories to seek public funding. This does not necessarily mean that the government is being asked to support work that is not worth supporting. As stressed in Chapter 3, the social value of the technology may exceed the return which a private

developer can capture, and an investment which offers inadequate prospects to attract private financing may remain quite attractive as a social investment. But the situations in which public investment are most warranted even though private investment finds the venture inadequately promising tend not to be those in which near-term commercial applications are clearly available if the program is successful, aside from the inherently risky possibility of EV applications.)

Several cautionary points may be noted regarding nickel/zinc technology. From the sketchy data that has been released, it appears that there may be severe power/energy tradeoffs at high power levels for these batteries. (Apparently, the developers themselves remain quite uncertain about the performance tradeoffs that might be involved in commercial versions of the battery.) And costs (per storage capacity) are unlikely to be lower than those of current lead/acid batteries. Although a marginally satisfactory ("shoulder of the curve") passenger car in terms of performance may evolve from this technology (possibly a hybrid), barring severe constraints on fuel availability, a significant market for such cars would still require heavy subsidies.

Some numbers will give some feeling for the subsidies likely to be required. Assume both that gasoline prices rise to \$1.20 per gallon and what appears to be an optimistic 5¢/mile cost for batteries derived by GRC from developers' estimates [101, Task Report 9, p.13]. For comparable cars (aside from EV range limitation) Table 7.1 indicates that about 3¢/mile subsidy is still needed to equalize total cost per mile for the two cars. An additional 1¢/mile is a conservative estimate of the additional subsidy needed to offset the fact that the car is only "almost competitive" with a conventional car, not fully competitive. The car has a still-significant range problem.

This comes to \$400 per year for a car driven the typical average of 10,000 miles per year. (As noted earlier, assuming the car will be marketed to low-mileage users does not necessarily improve the economics.) Note that this is not a one-time subsidy at the time of purchase, but \$400 every year over the estimated 12-year life of the car.

Even this may be far too little, not only because it is based on clearly optimistic assumptions, but because, on those assumptions, a new battery costing about \$3000 is needed for the car every four years. (The new car cost of the nickel/zinc EV is divided almost equally between the cost of the battery and the cost of the rest of the car.) Would many people, even given the subsidy, spend \$3000 to refurbish a 5-10 year-old car?

Consequently, even granting the various grounds for subsidizing EV's noted in an earlier section, the prospect for an interesting role for nickel/zinc private cars appears very dim, particularly where incentives for stimulating the development of the industry could be provided in the far more plausible context (for reasons reviewed in Section 7.4) of commercial vehicles for specialized use.

Note that the enthusiasm of the privately-funded developers does not require that there be a significant application to electric passenger cars. Essentially what they hope to achieve is a battery which costs no more than current lead/acid batteries (for given capacity) but which weighs half as much. These investments could produce a handsome return even if there is no application as the prime energy source for passenger cars, or even to the more tractable (but limited, and as yet ill-defined) application of specialized fleet operations.

Summarizing the discussion so far, we may conclude:

Current Systems - Current lead/acid technology is inadequate to power a reasonable substitute for a conventional car, even assuming we are considering only a second car for urban use, and largely neglecting cost. So far as we can see, the belief often encountered to the contrary depends crucially on the understandable, but quite unwarranted, assumption that the nominal range of these vehicles is in fact a reasonable approximation of their practical range. A demonstration of this technology is almost certain to produce disillusionment rather than enthusiasm for electric cars.

A more reasonable urban car can be built using nickel/cadmium batteries, and an "almost competitive" urban car can be built using silver/zinc batteries. But the costs per mile would be so high (a factor of 2 or more greater than a comparable conventional vehicle) that the demonstration is scarcely likely to make the electric vehicle credible to the public. (For the silver/zinc vehicle, there would also be a non-crucial problem of protecting the cars from theft.) More plausible applications of current technology, even in a subsidized demonstration program, lie in the area of specialized fleet operations.

Near-Term Systems - The two possibilities which have been widely discussed are a greatly improved lead/acid battery and a more economical nickel/zinc battery. At least two major firms (Gould and GM) have announced that they are well along on nickel/zinc development programs. If the nickel/zinc technology proves to be successful, these batteries will be markedly superior to current lead/acid technology at comparable prices, but nickel/zinc cars still require large subsidies of the order of several hundred dollars per year (for the life of the car) to achieve any significant place in the private car market at gas prices of \$1.20 per gallon. They may prove to be competi-

tive (or competitive with relatively modest subsidies) in some fleet applications, even at current gas prices, and they may contribute to the viability of hybrid technologies. One must be markedly more pessimistic about the dramatic improvements occasionally claimed in prospect for lead/acid batteries, and particularly concerned that claimed potential advances in power or energy density may not be achievable without degradation of other aspects of battery performance or cost. While radical improvements in this mature technology are not impossible, they would be surprising.

7.5.3 Advanced Batteries Prospects

To reach capabilities which have at least the potential for a significant national impact on petroleum conservation, (without obviously requiring either massive subsidies or an intense fuel shortage) we must look to radically different kinds of technology, of which the most widely discussed for electric vehicle applications are fuel cells, the zinc slurry battery, the zinc chloride battery, and several types of high temperature batteries.

1. Fuel Cells - We have little to add to the many available discussions of fuel cell technology, other than to note that our inquiries in the U.S. and among developers in Europe have indicated a general mood of pessimism, and a consequent tendency to focus funding elsewhere. The basic problems remain those that have been faced for many years: fuel cells which use reasonably inexpensive fuel (e.g. hydrogen) require expensive catalysts, such as non-trivial amounts of platinum; fuel cells which avoid the use of expensive catalysts, require expensive fuel, such as hydrazine. The prevailing pessimism stems from the lack of promising research approaches to dealing with one or the other of these problems. So the situation remains that fuel cells are

potentially interesting, but for the foreseeable future are likely to remain economically unfeasible.

An important but secondary problem is that fuel cells (barring another kind of breakthrough) are quite severely limited in power density, hence requiring an unreasonably large volume and weight of cells to provide sufficient power for automotive applications. The reason this problem is secondary is that, given a breakthrough on the basic economics of fuel cells, they would become an attractive component of a hybrid using batteries, flywheels, or some other stored energy source for peak power requirements. In particular, a fuel cell/battery hybrid -- since both power systems would be electric -- would be relatively easy to build.

2. Zinc Slurry Battery - This is a form of zinc/air battery (or so-called because oxygen taken from the air is a component of the reactions involved) in which finely divided zinc powder is suspended in a liquid forming a slurry which is pumped through the battery. Power densities appear to be limited, but somewhat better (at acceptable energy density levels) than fuel cells. There has been a good deal of interest in this kind of battery as applicable to a modest-performance urban car. Depending on the performance actually achieved, a successful development along these lines might reach our "shoulder of the curve" performance; or it might (like the fuel cell) be an attractive component of a hybrid.

At the moment serious work on this concept is largely abroad, principally by Sony in Japan and in several French laboratories. In the U.S., at least, there is considerable pessimism about the prospects, largely because of the disappointing results of efforts, funded by utilities here, to develop zinc/air batteries for load leveling.

The great advantage of the zinc slurry approach is that the battery is recharged by changing the slurry, an operation (hopefully) not much more time-consuming than refilling the tank of the conventional car. However, the logistics are more complicated than with conventional fuel (the old slurry must be drained and reprocessed), and the range between refills will be very short compared to a conventional vehicle, which can easily be provided with a fuel tank giving 250 miles of range between visits to the service station, compared to 50 miles or so for the zinc slurry battery.

But, assuming refilling stations are widely available, the problems of practical range stressed in our previous discussion are enormously erased. For on occasions where actual range turns out to be well short of nominal range, the driver faces only a stop at a service station, rather than creeping home on inadequate power or requiring a tow. Should this technology actually become available, there would be an obvious role for the government (should it be deemed in the public interest to encourage adoption of the technology) in subsidizing the early stages of developing the refilling station network required. Until the technology becomes available, the question remains moot.

3. Zinc Chloride Battery - The key to this system is maintaining the required chlorine in a frozen compound, which requires that the temperature be kept below 8° C (15° F). Hence the system is mechanically rather complicated, requiring a refrigerator and auxilliary pumps. The technology has the potential, though, (unlike any discussed so far) of providing a combination of power density and energy density clearly beyond our "shoulder of the curve". The work is supported by a consortium of Occidental Petroleum and Gulf+Western with significant participation by Gould. It is clear that Gould, at least, has become disillusioned with progress to date. Aside from the complexity

of the system, and the obvious need for careful measures to deal with the possibility of a breakdown of the refrigeration system (which would initiate the release of chlorine gas), the system faces a complex fundamental problem which to date does not seem to have been resolved: no satisfactory method of recharging the battery has been demonstrated. Until this is accomplished, the system remains completely impractical for its intended automotive application. (This points up one of the difficulties with "demonstrations" in which what is being demonstrated has not been clearly defined in a useful and promising way. A zinc/chloride powered vehicle was impressively demonstrated as long ago as 1971; but the demonstration was rather meaningless in the absence of any practical way to recharge the battery.)

4. High-Temperature Batteries - Many previously unexplored combinations of materials with high electrochemical potential have been considered in recent years in work which accepts the difficulties of working with ordinarily solid materials in a molten state. The attraction is the possibility of order-of-magnitude improvements over lead/acid performance: any number of these combinations have the potential of providing a car battery which provides competitive performance to a conventional car together with nominal range (possibly approaching or exceeding 200 miles) which is clearly beyond our "shoulder of the curve" and at a cost that might be competitive with a conventional car even at current gas prices. The prospective economies come partly from the use of inherently cheap materials, such as sulphur; partly because the performance is so good that a relatively small mass of material is required. If the developers' goals are achieved, these vehicles could conceivably save a cent or more per mile over conventional cars (total operating costs), aside from whatever social value is attributed to relieving de-

pendence on petroleum. But the complexity of the technologies leaves both the achievability of the performance goals in a practical design, and the details of the economics, very uncertain.

The fundamental technical problems facing all high-temperature battery programs concern materials: chemical reactions are characteristically accelerated at high temperatures. This (in part) is the source of the high potential performance of these batteries. But it introduces severe problems of corrosion as well as other modes of deterioration of the battery materials. Beyond this, there are critical design problems to handle the insulation requirements of these batteries; to assure that the battery is not severely damaged should the materials be allowed to solidify, as must be at least occasionally anticipated in automotive applications; to assure reasonable safety standards in the event of a crash; and so on.

Work to date on the high-temperature batteries has been stimulated primarily by the potential market for load leveling batteries for the utility industry. This is an inherently easier technical problem than the automotive application. The batteries would be stationary; they would have highly predictable duty cycles; modest power densities are quite adequate; the safety and maintenance problems inherent in an automotive application are greatly eased; and so on.

We may conclude with a few comments on the two leading candidates for a high temperature battery, lithium/sulphur (in which the leading role has been played by ERDA's Argonne National Laboratory) and sodium/sulphur (developed at Ford). It is first worth noting that the Argonne and Ford batteries involve very different technologies: in the Argonne (lithium/sulphur) battery, and variants being pursued elsewhere, including GM, the electrolyte is molten;

the electrodes themselves may not be (a point we will return to). In the Ford battery, the electrodes are molten, and the key to the technology is a porous ceramic (beta alumina) solid electrolyte, which separates the molten electrodes but allows the migration of electrons across the interface.

The particular development which is the current focus of interest at Argonne uses solid electrodes, which considerably compromised the ultimate potential of the battery. This represents an important redirection of the program several years ago in the face of technical difficulties. Thus, at the moment, the potential of the Ford battery is superior, and it is perhaps not surprising to find that more laboratories are following the Ford lead than that of Argonne, some using beta alumina, others experimenting with alternative solid electrolytes. An important, but not necessarily conflicting, exception is GM, which has a substantial effort on the Argonne type of battery, but focused on the more difficult molten sulphur version (under the direction of the former leader of the Argonne program).

The Argonne program is, of course, fully funded by the U.S. Government. The Ford program is primarily funded by the U.S. Government, currently through NSF support, with ERDA support planned in future years. An important effort in Britain on sodium/sulphur batteries is government-funded. Numerous smaller efforts are underway around the world, with some mix of public and private funding.

In sum, then, a considerable number of potentially "reasonably competitive" batteries are in principle feasible; substantial efforts are underway on two basically different types of high-temperature, high-performance, batteries, with numerous more modest efforts here and abroad exploring variants or alternatives to these efforts; all face difficult technical problems and

it is likely to be several years before confident estimates could be made of when (or if) these efforts will produce the kind of battery that would make a significant market for electric cars plausible. Finally, as with all the advanced battery technologies, early automotive applications are likely to come in highly specialized roles, not in vehicles suitable for the passenger car market. The battery discussion just concluded is based primarily on our interviews with research workers in the field. General reviews, several years old but not significantly out of date, may be found in [112,113,114].

7.5.4 Non-Battery R & D

The discussion so far has been concerned solely with battery development. But the cost and performance of electric vehicles will be affected by many other aspects of vehicle design and equipment. We provide a brief discussion. It is useful to distinguish among several categories of possible other-than-battery R & D:

1. Developments unique to the EV, as contrasted to developments common to many automotive applications. The key items of the former category are electric motors and their associated controls. Key examples of the latter are low-friction tires and body designs which minimize aerodynamic drag.

2. Development which can be effectively pursued independently of total vehicle design as compared to those which cannot. For example, work on low-friction tires would be independent of overall vehicle design, but work on body design to minimize drag would interact with requirements imposed on the vehicle: both those which apply to vehicles generally (for example, safety regulations requiring side mirrors), and those associated with the volume, shape, and weight requirements for a particular battery, especially as they

interact with safety and maintenance constituents.

3. Advanced development and production engineering as contrasted with research and exploratory development. For example, refinement of an existing motor design to optimize it for EV application, vs. development of a novel type of electric motor uniquely suited to the EV application.

4. Rapidly evolving technologies as versus mature technologies. For example, advances in controllers for EV probably would rely heavily on advanced solid state electronic technology, a rapidly evolving field. A new motor, though, would primarily involve adapting a mature technology to optimize a motor for the EV application.

All of these distinctions tie into the issue of whether R & D should appropriately be focused on long-lead-time efforts or short-lead-time efforts. If it were realistic to believe the acceptable mass-market EV's could be ready for production within 5 years, then a substantial effort on short-lead-time efforts would be justified. One might decide to fund a program to develop an advanced controller using today's solid state technology, for example. On the other hand, if it is unrealistic to believe that an acceptable mass market EV could be produced in less than ten years, then an effort of that kind might well be a waste of money: solid state technology continues to evolve so rapidly that a device based on current technology is quite likely to be obsolete by the time the occasion for its use arises.

Similar considerations arise on the other issues. Particularly important is the contrast between engineering development and production engineering as versus more basic R & D. It is, by far, the former which requires the heavier investment for such things as detailed design, pilot plants, and elaborate test facilities. A few million dollars a year may be quite signif-

ificant funding for advanced R & D; it will be a drop in the bucket compared to the investments that would have to be made in the late stage of the R & D process.

Having in mind these points, a few comments seem in order:

1. The summary of battery issues presented here reflects our impression that there is a strong concensus of opinion in that portion of the technical community in the best position to make such judgements. Naturally, variations on individual points abound, and perhaps even more naturally, one finds that individuals associated with particular technological efforts tend to be relatively optimistic about their own work and relatively more pessimistic about work that is competitive with their own. Nevertheless, there seems to be a broad and well-founded consensus that a mass market vehicle employing advanced batteries could hardly be produced in less than 10 years (i.e. by 1985) no matter how urgently the technology is pushed and how generously it is funded. Thus important impacts from current R & D on advanced batteries, if they are to come, should realistically be judged to lie beyond 1985, and more probably not before the 1990's.

2. There is much less consensus on the question of whether advanced batteries are in fact required to make a significant role for EV's possible. For example, currently proposed legislation [108] would finance a rather large scale (several thousand vehicles) demonstration of the commercial feasibility of current and near-future state-of-the-art EV's, including passenger cars, over the next 5 years. The Committee Report notes that "a significant limitation of today's electric vehicles is their range, which is typically about 50 miles . . . However, even this short range is adequate for all (approximately 98 percent) of the daily travel of the 'second' car". [] The

premise of the bill is that an acceptable urban second car is within reach in terms of performance and reasonably within reach in terms of economics, especially if use is subsidized to take account of the social value of the vehicles and of economies of scale once mass production has begun. There are currently something like 20,000,000 cars in this country which might be considered urban second cars. Hence, provided the premises of the legislation are correct, the demonstration could lead directly to a substantial mass market for electric cars in the early 1980's.

Judgements on the appropriate role for Federal R & D will differ radically, depending on whether one accepts the premises just outlined. If so, then it seems appropriate, and indeed necessary, to spend a major share of Federal R & D support on work that will pay off over the next several years, allowing for its incorporation in the vehicles that will be built and demonstrated within a relatively few years. It would be very important to make whatever improvements can be made over the existing vehicles to enhance the success of the demonstration, and to lay the ground for the large scale commercialization expected to follow the demonstration.

On the other hand, if the premises underlying the demonstration are deemed unrealistic, then equally clearly whatever portion of the \$160 million proposed demonstration program is allocated to R & D is likely to be very inefficiently allocated to near-term improvements of a technology which will remain gravely inadequate. The work is likely to make very little contribution to more advanced vehicles which might be available in later years (post-1985 and perhaps more realistically, post-1990).

On the alternative premise (that a mass-marketable electric car requires radical advances in battery technology), such R & D as is funded on work other

than advanced batteries should be focused on developments which require long-lead-times, in areas where technology is not moving so fast that work begun now is likely to be obsolete before advanced batteries are available, and where the broader pressure to improve fuel economy by weight reduction and streamlining (hence reducing power and energy requirements) will not as a by-product provide the R & D needed for the EV application.

In sum then, appropriate allocation of R & D work other than batteries will vary sharply depending on what view one takes of the prospects of near term EV's. Our own views have been indicated in the discussion which is summarized in the section below.

7.6 The Electric Vehicle: Summary and Conclusions

- 1) Over the long run (25 years or more) electric vehicles are an important, though not assuredly viable, prospect: and it is important to note that this conclusion does not depend on current policy with regard to new sources of liquid fuels, such as shale oil or synthetic oil. For the costs, political feasibility, and realistic scale of such supplies are necessarily very uncertain. To the extent that electric vehicles succeed in penetrating the vehicle market, this is likely to be a welcome complement to a new fuels program. And, of great importance, creation of an EV option provides an insurance policy in the event that pessimistic appraisals of liquid fuel availability prove justified.

- 2) Although a substantial market for electric cars is not assured

even assuming success on development of radically improved batteries, the prospect is sufficiently attractive that a good case can be made for Federal encouragement of an electric vehicle industry (with the important qualifications listed in the subsequent point). Such encouragement would serve two important functions:

- a. Unlike other alternatives (such as the Stirling or gas turbine engines), electric vehicles require broad changes in the infrastructure of the transportation system. Although the prospect of complete conversion to electric propulsion lies in the remote future any substantial usage of electric vehicles implies important changes in supporting infrastructure ranging from numerous regulatory details to provision of wiring suitable for recharging in housing and public facilities. The problem is not that there are a few big things that are needed but rather a myriad of small things. An initially small but growing electric vehicle industry will encourage these adaptations, and ease the conditions for a substantial scale transition when the technology arrives.
 - b. Although, as has been noted many times, the crucial problem for electric vehicles is the evolution of radically improved batteries, numerous other details of electric vehicle systems would benefit from technical advances. Public encouragement of the development of an electric vehicle industry may well be a more efficient way to stimulate such across-the-board advances than public investment in component R & D, at least until battery development is farther along than it is today.
- 3) But the least promising area for government efforts to stimulate an electric vehicle industry is in the field of private passenger cars. As we have tried to show in some detail, private cars with current or near-term battery technology are unlikely to be competitive with conventional cars unless massively subsidized. The frequently noted favorable comparisons between the nominal

range of current technology electric cars and typical urban driving are quite drastically misleading. The desired growing industry suggested in the previous point seems least likely to evolve in the foreseeable future if the effort is focused on passenger cars. Rather, fruitful efforts along these lines almost certainly must be focused on specialized fleet applications of electric vehicles: and indeed the number of promising opportunities for reasonably economic applications of EV technology is likely to be very limited in the immediate future. What is needed most clearly is a serious planning effort, not an immediate action program. Just where might early applications come? What kinds of specific programs look promising?

- 4) With regard to battery R & D, the most important point is that only advanced batteries appear to have plausible potential to achieve significant market penetration in the passenger car field, and of course it is only in the event of significant penetration of the passenger car markets that EV's can make an important contribution to fuel conservation. But two independent (basically different technologies) advanced battery efforts are currently supported by the Federal Government. A third substantial effort (an adaptation of one of the American technologies) is underway in Britain, and what currently appear to be somewhat less promising efforts are underway in Japan and France. Progress on each of these efforts has been slow, but so far as we have been able to determine, not importantly

limited by funding limitations. Thus it is not clear that an immediate increase in funding for battery research would significantly improve the prospects for a viable technology.

(Clearly, much more money will be needed once an advanced battery is ready for engineering and production development.) However, since the amounts of money are small compared to the prospective gains and compared to other energy-related efforts, a reasonable case can be made for providing funding for one or more additional substantial efforts, selected as the most promising from among the many currently small-scale efforts in private industry. This applied R & D work should be accompanied by well-supported fundamental research.

With regard to near-term battery R & D (notably improved lead/acid and nickel/zinc batteries), which would have to power the early applications of EV technology suggested above, it appears doubtful that Federal support has an important role to play, for there are sufficiently large non-automotive markets for these batteries to encourage substantial private investment. The incentive for private investment would, of course, be enhanced if public encouragement for early applications was assured.

- 5) An important point of detail which is worth noting here is that the view that a viable electric passenger car must necessarily be one capable of recharge with the convenience of refilling a gas tank seems unwarranted. Obviously, the prospects for electric cars would be greatly enhanced were some approximation of "instant recharge" feasible. No realistic prospects on this line are

evident. But the importance of "instant recharge" diminishes as the range of the vehicle increases, and as (consequently) the likelihood diminishes that a recharge will be needed other than at times very convenient to the user (notably, while parked overnight).

- 6) In sum, then, we believe that the electric vehicle is an important prospect for the long run and an important insurance policy hedging against liquid fuel shortages and/or very high fuel cost; consequently, we believe that it is well worthwhile to generously support R & D on batteries and fundamental research that promises to be applicable to electric cars. We believe that it would be appropriate to undertake a planning and policy analysis effort looking towards government-encouraged applications of electric vehicles within a few years, with a focus on specialized fleet applications rather than passenger cars. But we also believe it is important to be realistic about the time-scales and problems involved, and that (even more than with other technologies reviewed in this study) an attempt to produce dramatic short run results is likely to be disillusioning and wasteful.

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APPENDIX A. HISTORY AND STATUS OF STIRLING ENGINE TECHNOLOGY

In Section 5.2 we gave a brief description of the key features of the Stirling engine, an organizational history of the important past and present Stirling R & D programs and a summary of the system's potential attributes in the next decade. In this appendix we supplement Section 5.2 by describing the past and present technological content of the R & D programs (Section A.1) and then discussing the key features and components individually and their present status (Section A.2).

Some of the material presented in Chapter 5 will be repeated here when necessary for maintaining the continuity of the exposition. Much of the historical material presented here is taken from personal interviews at the organizations involved.

A.1 Technological Review of R & D Efforts

A.1.1 Philips and Ford

As discussed in Chapter 5, work on the Stirling engine by N.V. Philips Gloeilampenfabrieken has been underway more-or-less continuously since 1938, at the Philips Research Laboratories in Eindhoven, the Netherlands. The initial program was designed to provide a quiet source of electric power generation for use at remote sites, a need eliminated by the advent of the transistor.

Research was continued, however, and numerous engine configurations were examined in the post-World War II period. A major breakthrough was made in 1953 with the invention of the rhombic drive. This is an ingenious gear and rod system for coordinating the movements of two pistons in a

single cylinder engine, and resulting in a rotary power output at a crankshaft. Before this time Stirling systems required extremely complex rocker arm assemblies so that the two pistons would be coordinated. Figure A.1 shows a cross-section of a Philips engine of the 1960's. Each piston is "single-acting;" the "power piston" principally serves to draw power from the heated working gas, while the "displacer piston" principally serves to move the gas between the heater and cooler. Each cylinder is practically an independent engine; because the rhombic drive provides for almost perfect balancing large single-cylinder engines are possible. The major disadvantages of the rhombic drive are that it is very bulky and heavy, the drive mechanism takes up about as much space and weight as the sealed working gas system itself. During the period 1953 to 1965 Philips focussed on basic engineering studies and component development for the single-acting rhombic drive system. A key event during this period was the development in 1960 of the roll-sock seal, a fully lubricated rolling diaphragm, to meet the requirement for a gas-tight external seal between the piston rod and the cylinder base. As automotive air pollution began to be perceived as a serious problem in the United States, Philips began to seriously consider the Stirling as a potential competitor with the diesel in the heavy duty prime mover field. A 4-cylinder engine was installed in a bus as a demonstration of the low noise, vibration and emissions, and competitive efficiency of the system.

However, with active consideration of the prime mover application, interest was renewed in alternative configurations to the bulky single-action rhombic drive system; alternatives which would achieve a system power density (ratio of power output to total system weight or volume)

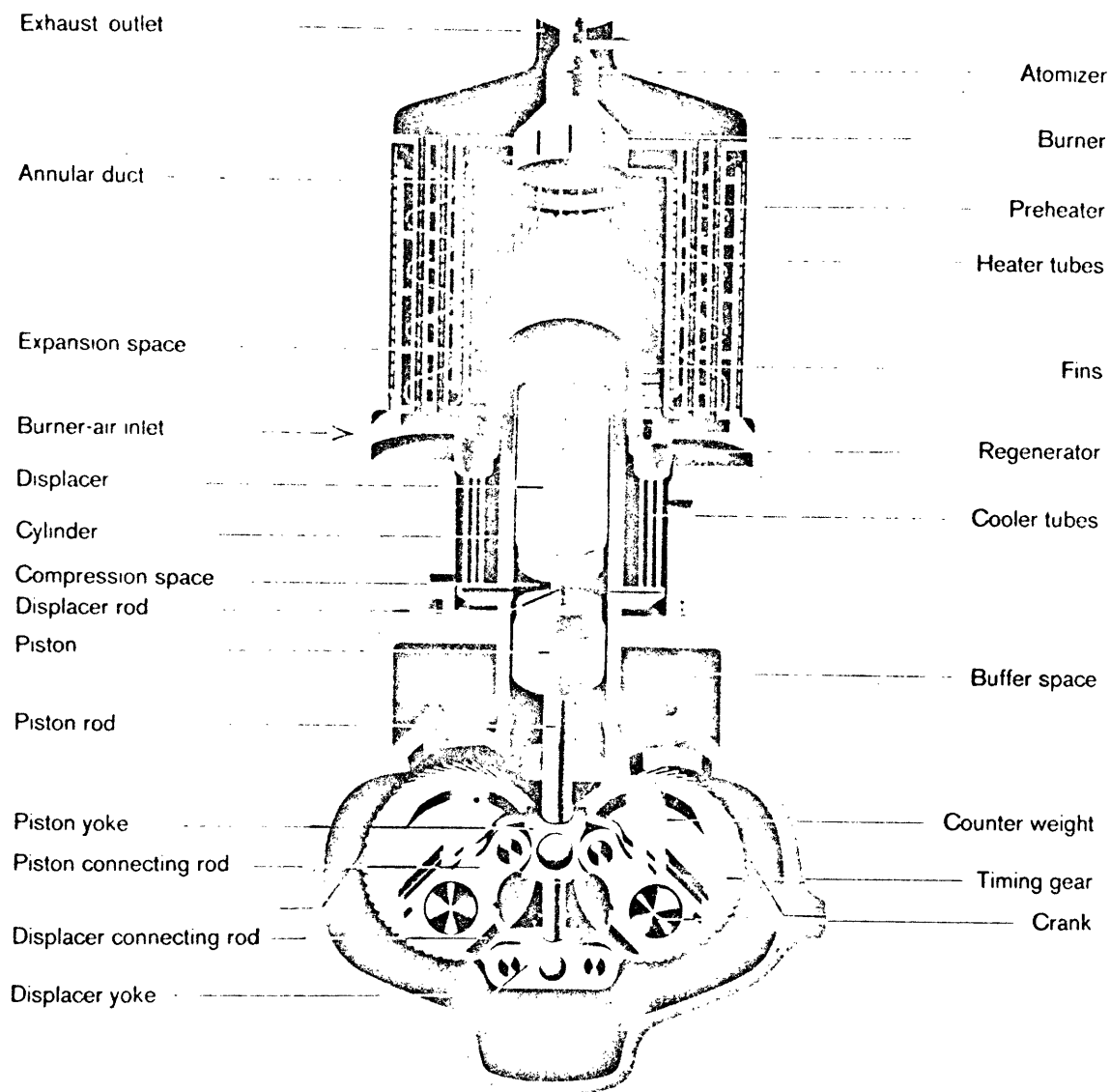


Figure A.1

CROSS-SECTION OF PHILIPS
 SINGLE-ACTION RHOMBIC
 DRIVE STIRLING ENGINE [1]

competitive with the diesel. In 1968 an engine with double-acting pistons and a swashplate drive was designed and (subsequently) built. It was similar to that shown in Figure 5.1 in the main text. In this configuration there is only one piston per cylinder; a number of cylinders are cyclically interconnected and the working gas alternates between the upper half of one cylinder and the lower half of an adjacent one with the heater, cooler and one or more regenerators in between. The swashplate drive consists of a circular plate obliquely connected to a shaft, the piston rods from the piston's are connected to the edge of the plate by sliders, so that the reciprocating rod motion is converted to a circular motion of the plate and thus the output shaft. The double-action swashplate system represents a substantial improvement in overall specific power over the single-action rhombic drive system. A key development which helped to renew its attractiveness had been the development (unrelated to the Stirling program) of Teflon; from which internal piston seals which required no lubrication could be made. This double-action swashplate engine was the direct forerunner of the present Ford prototype.

A number of Philips' important developments should be mentioned here. First, all working gases other than hydrogen were eliminated from practical consideration. The theoretical advantages of hydrogen had long been known; Philips' advances in seal technology allowed the highly diffusive gas to be contained in working systems; although direct diffusion through the metal itself remained a problem. The power control system developed by Philips is based on changing the mean pressure of the working gas by pumping it between the engine proper and a high pressure storage reservoir. Philips also developed extremely efficient regenerators. Finally, along with the

continuing experimentation discussed above, Philips developed an extensive set of component analyses from which they have created a sophisticated computerized capability for engine synthesis.

In summary, Philips has carried the Stirling engine from its status as a museum piece in 1938 to the point where laboratory prototypes demonstrated the size, weight and performance features expected of modern automotive power-plants. On the order of a dozen different engines, some in many copies, were built, on which a large number of components were tested and refined. The total number of engine hours accumulated has not been released, but probably approaches 100,000.

The technology used in the Ford-Philips program is essentially that which has been distilled out of Philips' long efforts and is now available as most appropriate for this particular application. The horizontal, four cylinder double-action configuration with the swashplate drive is similar to an engine previously built at Philips. The power control system utilizing mean pressure variation and a bypass for rapid response, the roll-sock seals, and most other crucial features were originally developed on the single-action rhombic drive systems. The only important new features are the use of exhaust gas recirculation in the burner for NO_x reduction, and a new proprietary coating recently developed by Philips to greatly decrease the diffusion of hydrogen through the metal walls. Ford arranged with United Stirling for the mounting of a small test engine in a Pinto in the summer of 1974 for a very preliminary set of passenger car tests.

The Ford engine program presently consumes the bulk of Philips' Stirling effort. However, Philips has also been examining a number of potentially major advances in Stirling cycle technology. First, Philips is

working to both decrease the cost of the heater head and raise engine efficiency by use of ceramics in place of the present superalloys. However, Philips is also looking for ways, short of complete replacement of all possible high-temperature components with ceramics, to accomplish this. For example, they are looking at the possibility of cooling the outer surface of the cylinder dome with water, and lining the cylinder inside with a ceramic. For several years, Philips has been examining the use of a heat store with the heat pipe. A third area which Philips has begun to look at is the use of a variable-angle swashplate for power control. Changing the swashplate angle changes both the swept volume and dead volume, providing an amplified power control. While this would require a complicated mechanical control of a load-bearing component, it would eliminate the need for a torque converter or other transmission components external to the engine. Combined with a heat-store, heat-pipe system, the variable swashplate would provide the capability of a high power (but low efficiency) transient operating point (present systems are limited in power by the combustion air blower output).

A.1.2 United Stirling

As discussed in the main text, United Stirling was founded in 1968, and initially hoped to develop as rapidly as possible an engine based on the technology then most prominent at Philips, i.e., single-acting power and displacer pistons, rhombic drive, roll-sock seals, etc., and to market it for uses where the advantages of high efficiency, clean exhaust, and low noise and vibration would outweigh the relatively high initial cost. It had been hoped that the submarine, city bus, and underground mining equipment

might provide such applications. The 200 hp engine which resulted in 1971 turned out to be too heavy and expensive even for these markets, although it did have low noise, vibration and emissions, and a thermal efficiency somewhere between that of an ICE and a diesel.

With this experience, the company then decided to orient its development work more specifically toward the prime mover field, where the increasingly stringent emissions and noise controls would tend (they hoped) to increase the attractiveness of the Stirling relative to the diesel. The second major design effort then was a double-action engine in the V-4 configuration with cross-head pistons and a standard crankshaft, producing 40-60 hp, shown in Figure A.2. The idea was to stay as close as possible to conventional prime mover technology in order to minimize development and production costs and to take advantage of the higher specific power of the double-action system. The first prototype of this engine was produced in late 1971; six were built in all. At the present time, United Stirling is focusing its efforts on a 100 hp, double-action V-4 engine, which will be designed and built in a 200 hp, V-8 configuration as well. One such V-4 model has been running in a test cell since late 1974. This latest model differs from Philips' most widely used technology in several important areas: its use of sliding seals as compared to the roll-sock, its conventional "V" configuration and crankshaft as compared to Philips' in-line single-cylinder geometries and rhombic drive, its use of double acting pistons as compared to single-acting power displacer pistons and its variation of dead-volume as compared to mean pressure for power control.

This 200 hp engine is now in what United Stirling has designated its "Stage Zero", and achieves a thermal efficiency about halfway between that

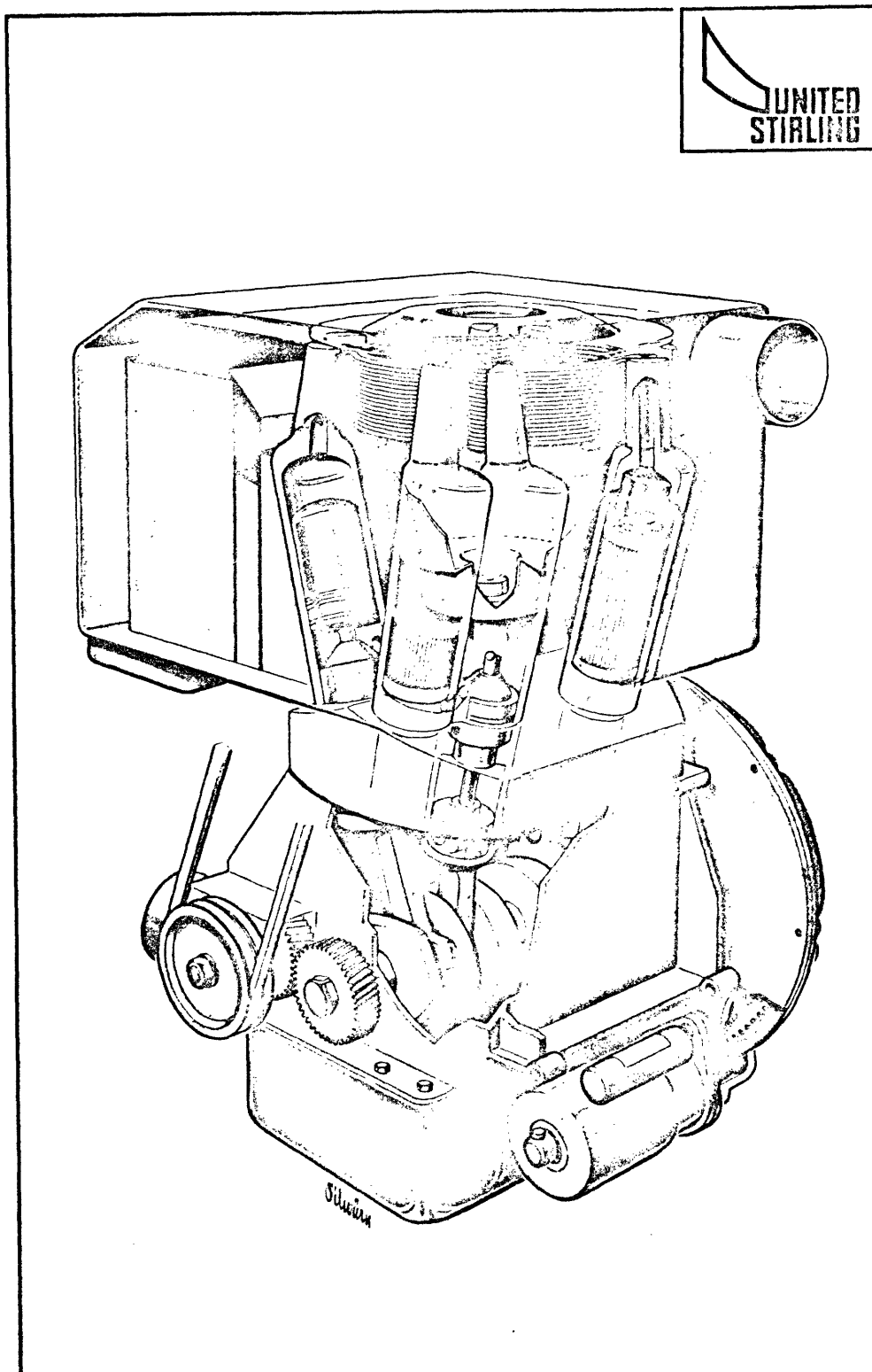


Figure A.2

CUTAWAY DRAWING OF UNITED
STIRLING DOUBLE-ACTION V-4
STIRLING ENGINE

(Courtesy of United
Stirling (Sweden))

of the present ICE and diesel. The engine at "Stage One" is planned to have a thermal efficiency closer to that of the diesel using improved versions of present technology, and it is hoped that this can be demonstrated in a prototype within a couple of years. This engine would (they hope) compete with the diesel where special requirements such as noise or emissions control would make the Stirling more attractive in spite of its higher initial and operating costs. The company sees the Stirling fully competitive with the diesel only in their "Stage Two" when, using ceramics rather than high temperature steel for the critical hot components, the Stirling engine would attain a thermal efficiency equal to the diesel's, and a considerably lower first cost. This will not be obtained even in the laboratory for four to five years; a ceramic component development effort is just now getting underway. A separate effort on the use of heat pipes with the engine to both reduce cost and improve efficiency by permitting much higher heat transfer fluxes to the heater head is underway.

While United Stirling's efforts are focused on specific engine configurations which it hopes to improve and eventually market, the company has made a strong commitment to fundamental engineering studies of almost every component of the engine. Thus, in parallel with the specific development efforts discussed above, an impressive engineering and development capability has been developed. For example, studies of heat transfer coefficients across banks of closely spaced tubes, and flow visualization studies using water, are underway in support of heater head development. Simulator rigs for other key components have been constructed as well.

A.1.3 M.A.N. - MWM

The M.A.N.-MWM group has always had a long-range view of the Stirling engine's potential. They have therefore not sought to build a prototype for a specific application, in contrast to the efforts on Philips' Torino engine and United Stirling's V-8. In 1969 they designed and built a single cylinder 30 hp single-acting rhombic drive engine and a similar 4-cylinder version to gain design experience and to serve as test beds. They have designed and are now building a 4-cylinder in-line double-action crankshaft-drive engine. Their principal efforts, however have been put into developing the low cost, reliable component technology which would be applicable over a wide power range, preferably in a modular format. The group's most noteworthy accomplishment to date has been the development of a heater which can be precision cast at minimal addition to the materials cost. They have designed it to be as light as possible, and their testing has proven it reliable. It consists of a finned tube, a plain tube, and a connecting U-shaped tube, all of which can be brazed to the cylinder and regenerator housing. They claim to have achieved a cost reduction of 90% relative to the conventional Philips heater, due to a smaller high temperature metal requirement and the elimination of a special machining requirement. Optimization and testing of the unit continues.

Rather than the rotating ceramic regenerator which United Stirling and Philips are using in their latest designs, the M.A.N.-MWM group has developed an accordian-like recuperator, with hot and cool gases in alternate folds of metal. It replaces a number of welding operations with folds and thus is cheaper to manufacture than previous Stirling recuperators. It has the advantages of being easily replaced as a unit if it becomes blocked.

and of minimizing leakage between exhaust gases and incoming air. Both this recuperator and the previously discussed heater head can be combined directly into larger units with minimal redesign. The group's latest design uses a conventional crankshaft drive, rather than a swashplate, which would have required a separate development effort, or the rhombic, which is bulkier. It is an in-line configuration in contrast to United Stirling's "V".

Because of the two firms' interest in other applications as well as the automotive the Group has a different perspective on the requirements for the Stirling engine control system. For example, little output modulation is needed for the duty cycle of an electric power generator. Another present application of heavy duty diesels is in ship propulsion, where there is no need for rapid output changes, but the engine must maintain its efficiency for long part-load operations; the Philips mean pressure control system is adequate for this. The Group has not been able to achieve the part-load efficiencies claimed by United Stirling for their dead volume control system. The Group is working on a new type of control system which they claim will provide rapid response without the substantial loss during the transient which characterizes Philips' use of working gas bypass, but they will not discuss it in detail. It involves a working gas bypass carefully controlled as a function of phase angle. The Group has tested both roll-sock and sliding seals. Both have held up well under laboratory conditions; but they are concerned as to how they will perform in a working environment.

A.2 Technological Status of The Stirling Engine and Its Key Components

In Section 5.2 and the preceding pages of this Appendix we have defined the crucial features of the Stirling cycle powerplant and described the past and present development efforts aimed at bringing it to the end of the Initial Development Stage. In this section an attempt will be made to summarize and characterize the status of engine, its key components and features. As discussed in the previous section, numerous Stirling engines have been operated on test stands and a number have been demonstrated in vehicles of various sorts. Thus, for each important component there is at least one concept from which an operable engine can be made. In fact, there are several alternatives in most cases, and also there are varying degrees of development experience behind the alternatives and there are one or two "front-runners," which presently appear to have the greatest probability of utilization should the Stirling engine be commercialized at an early date, and there are advanced concepts which offer theoretical advantages, but lag behind the front-runners in development status. The distinction is a crucial one; the key attributes of a Stirling-powered passenger car depend on what set of alternatives is chosen; this in turn implies the extent of further development required and thus the likely introduction date. First, gross system design choices will be discussed. Second, the key individual components will be addressed. Table A.1 summarizes the discussion.

Table A.1

DEVELOPMENT STATUS OF KEY STIRLING ENGINE FEATURES AND COMPONENTS

<u>Feature/Component</u>	<u>Concept</u> (* = FGS)	<u>Prime</u> <u>Organization</u>	<u>Comment</u>
Configuration and drive system	Single-action rhombic drive	Philips	No longer considered viable - too heavy
	*D-A, Parallel cylinders, swashplate drive	Philips-Ford	
	*D-A, "V" or in-line cylinders, conventional crankshaft	United Stirling, M.A.N.-MWM	
Working gas	*Hydrogen	All	Key for power density; sealing problems
Heat Source	*Burner	All	Well developed
	Heat store	Philips, United Stirling	Limited range problem
	Heat pipe	Philips, United Stirling	Advanced concept
Heater head	*Metallic	All	Expensive
	Ceramic	Philips, United Stirling	Advanced concept
Power Control	*Mean pressure with bypass	Philips-Ford, M.A.N.-MWM	Inefficient during transients
	*Dead Volume	United Stirling	Expensive, complicated
	Variable-angle swashplate	Philips	Advanced concept

Table A.1 (Cont'd)

<u>Feature/Component</u>	<u>Concept</u> (* = FGS)	<u>Prime</u> <u>Organization</u>	<u>Comment</u>
External seals	*Roll-sock	Philips-Ford, M.A.N.-MWM	Durability unclear, catastrophic failure, hermetic seal
	*Sliding	United Stirling, M.A.N.-MWM	Difficult to make frictionless and tight
Preheater	*Rotating ceramic core	Philips-Ford, United Stirling	Chemical attack a problem
	*Metallic recuperator	M.A.N.-MWM	Expensive
Regenerator	*Stacked metal screens	All	Expensive
Cooler	*Metallic	All	Expensive

A.2.1 Gross Design Features

The crucial distinction among modern Stirling engine configurations is between the single-action and double-action systems. The single-action system with rhombic drive (shown previously in Figure A-1) was the system on which Philips did most of the crucial development work of the 1950's and 1960's, and which was originally utilized by the United Stirling and M.A.N.-MWM groups. The latter two groups and the Ford-Philips team have all now turned to double-action configurations whose superior system power density are more competitive with those of modern prime movers. The Ford engine uses four horizontal parallel cylinders, whose axes lie on and are equally spaced around a cylinder, and uses a swashplate drive. The latest United Stirling and M.A.N.-MWM designs use conventional "V" or in-line configurations with crankshafts. It seems clear at this point that the double-action system dominates over the single-action system wherever volume is limited. While there is much less experience with swashplate drive as compared to a crankshaft, there do not appear to be any major difficulties which might prevent its utilization. Thus, while these are several competing configuration-drive systems, several appear to be adequate for the passenger car engine. The only major innovation being considered in this area is the variable-angle swashplate, discussed below with power control systems.

There is little doubt that any commercially successful Stirling system will use hydrogen as its working gas. The next best choice, helium, could be used at a sacrifice of power density of about one-third.[2] Air is far worse. The most important problem with using hydrogen is the difficulty

in containing it under the high pressures required for Stirling engine operation. This is addressed below under the discussion of seals. The other problem associated with the use of hydrogen is its flammability. The actual amount of hydrogen in a Stirling engine is so small (less than 20 gm) that "there would be more noise than visible effect" [3,p.113] in an explosion. In any case, it would diffuse very rapidly, should it leak, and it must be compared relative to gasoline vapor which is highly explosive. However, the issue is a sensitive one and remains open. Ford has funded a study at the Stanford Research Institute to reduce the present uncertainty.

A closed cycle heat engine such as the Stirling engine can be operated from any source of heat at the requisite temperature. The most prominently discussed alternative to a burner is the use of a heat store, whose heat would be transferred to the heater head of the engine either by a heat pipe or some more conventional system.[4,5] A heat store is an insulated container filled with some material capable of storing energy in the form of heat, as a latent heat of fusion, sensible heat or both. Heat stores can be recharged; most likely electrical resistance heating would be used -- the gross features of the system thus becoming similar to an electric vehicle running off energy stored in a battery. Taking into consideration the efficiency of a Stirling engine with a peak cycle temperature at the minimum temperature of a lithium-fluoride heat store, a specific mechanical energy storage of about 200 wh per kg of LiF has been cited [5]; incorporating the necessary insulation and other ancillary features would reduce this substantially, probably to the point where the key performance issues discussed with respect to the electric vehicle elsewhere in this report become directly relevant.[3, p.198] It does not appear that a

vehicle operated by a Stirling engine powered from a heat store could compete for a substantial fraction of the American passenger car market; in any case such a system would have to be considered an advanced concept in terms of its development status.

A heat pipe is a device which can transmit large quantities of heat with a very small temperature drop and deliver the heat to a very small area; i.e. it can deliver a very high heat flux. Independent of the original source of the heat (burner, heat store, etc.), the high delivered heat flux would permit a relatively small heater head, possibly resulting in a substantial cost savings. Philips and United Stirling are conducting small development efforts to take advantages of this opportunity; it must, however, be considered as an advanced concept in an early state of development.

A.2.2 Key Components

A.2.2.1 Heater Head

At the present time this appears to be the most costly, and thus possibly a limiting, feature of the system. It must contain the working gas at pressures of over 200 atmospheres while being maintained continuously at temperatures above 1400°F. These cycle parameters, crucial to the high efficiency of the powerplant, can presently be attained only with the use of expensive "superalloys," special steels utilizing nickel and chromium, because of tremendous stresses (thermal and non-thermal) which must be sustained at high temperature. Up to ten lbs each of nickel and chromium may be required in the heater head steels. The heater head serves as the

heat transfer surface through which heat is transferred from the flowing combustion products on the outside to the flowing working gas on the inside. The high surface area required is presently attained by the use of many small tubes, a configuration extremely difficult to readily mass produce. A heater head from a mid-1960's Philips engine is shown in Figure A.3. While satisfactory heater heads have been made at substantial cost for the experimental engines used to date, it is clear that this component will be a major focus of future cost reduction efforts. One approach is obviously to attempt to design a head which can be separated into castable components requiring a minimum number of attachments to each other and to the engine; this approach has been pursued with some success by the M.A.N.-MWM group and will obviously be a key effort in Phase II of the Ford-Philips program. While it is far from clear at this time whether these programs can succeed, the metallic heater head must be considered the most likely candidate for incorporation into any Stirling system commercialized within the next 10-15 years.

An advanced concept which is the subject of considerable interest in the Stirling engine community is to make the heater head from a ceramic material. Carefully fabricated small pieces of ceramic have demonstrated the ability to attain the required local properties of enduring stress resistance at high temperature. A heater head ideally made from such materials could actually accommodate cycle parameters which would theoretically add 5-10 percentage points to the metal-based engine's thermal efficiency. Because the basic materials from which such ceramics are likely to be formed (silicon, nitrogen, carbon, etc.) are very low in cost, it is theoretically possible that a ceramic heater head could be manufactured

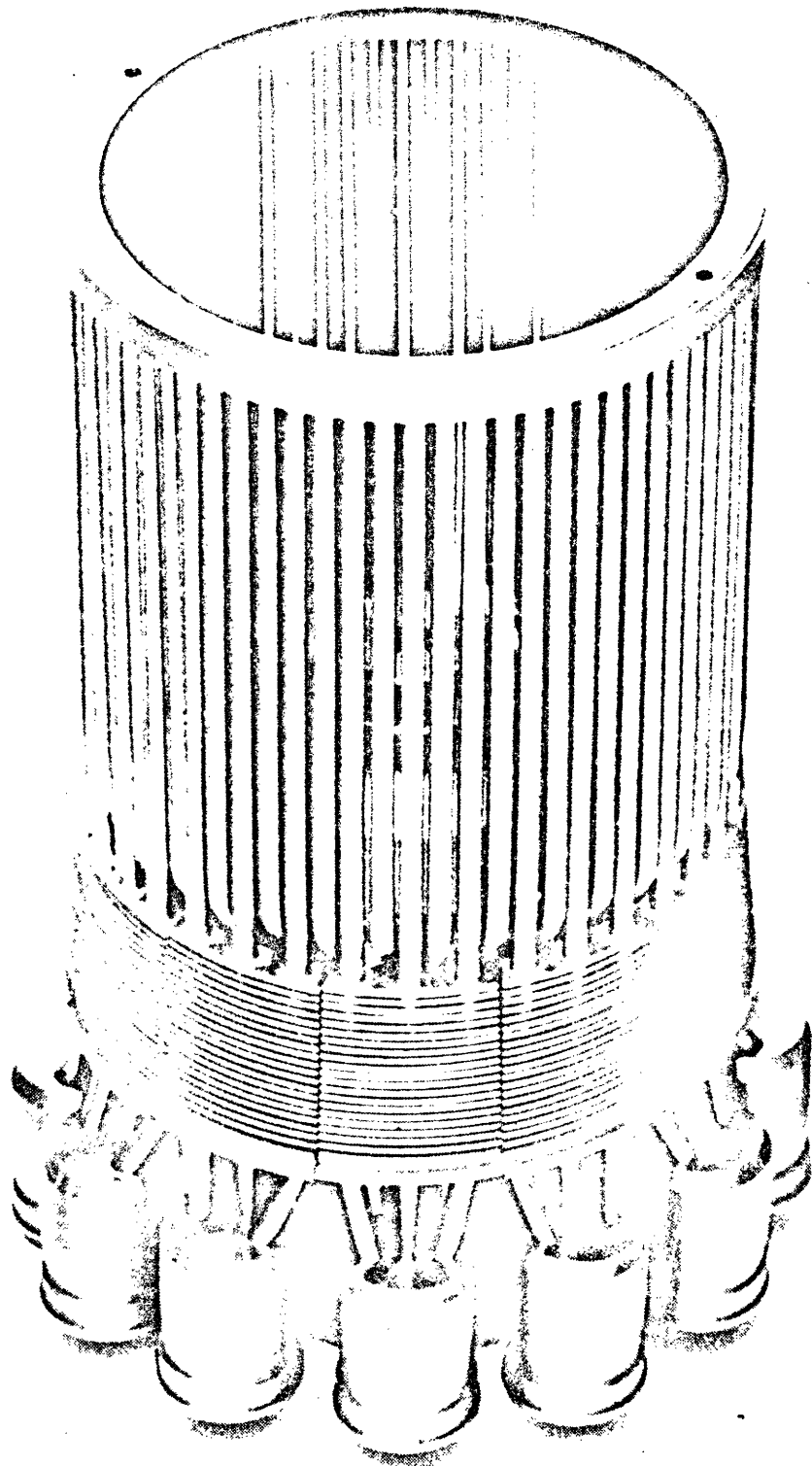


Figure A.3

HEATER FROM PHILIPS
STIRLING ENGINE [1]

very inexpensively. However, attainment of the ability to manufacture a satisfactory ceramic heater head would represent a major technological breakthrough. Ceramics are inherently brittle and tend to have a high concentration of local flaws. It is therefore extremely difficult to form engine-size components whose gross attributes for withstanding high stresses at high temperatures reflect the attractive theoretical local properties. Several programs are now underway to develop manufacturing techniques for high stress gas turbine components of ceramics: these programs are achieving limited success in meeting goals well short of those required for marketable machines.¹ The development of the capability to manufacture suitable gas turbine rotors or Stirling engine heater heads would represent a dramatic technological breakthrough with wide application in many areas (especially in power generation) and must be considered a long shot even for successful sustained dynamometer testing in an engine within the next decade or two.

Between the low-cost metallic and all-ceramic heater heads are a number of other possibilities, with varying degrees of probability of development success and possible degree of cost reductions. These include designs which reduce the use of superalloys through the strategic use of cooling jackets or ceramic liners. On the whole, then, while successful development of a low cost heater head remains a crucial feature of any

¹The present major American program is being supported by the Defense Department and managed by Ford. [6] The use of ceramic components in low stress components such as a Stirling engine (or gas turbine) preheater is much closer to success and can be considered a likely near term possibility as discussed below.

commercially successful Stirling engine program, there are a number of options which, if diligently pursued, may yield a successful device.

A.2.2.2 Power Control System

Power control is inherently more difficult for external combustion systems because the removal of the combustion process from the working fluid makes the fuel and air flows unsuitable as primary control variables; either some sort of variable system geometry or direct control of the amount of working gas in the system is required.¹ Philips' favored concept has been the latter: a reservoir of working gas is maintained at high pressure; power is increased by letting gas pass from the reservoir into the engine proper; to reduce power the gas must be pumped back into the reservoir. This is known as "mean pressure" control. Power increases are very rapid; power decreases with this system require an unacceptable length of time to pump the fluid out. In order to meet passenger care requirements, therefore, a simple bypass system is used momentarily to bleed gas from the high pressure section of the engine to the low. This is rapid but directly decreases engine efficiency during its use. The extent to which this is important depends on the duty cycle of the engine. The passenger car application requires a substantial degree of transient operation: the bypass therefore does cause some reduction in vehicle fuel economy.

¹The fuel and air flows must of course vary with power output; this does not appear to be difficult. The Ford-Philips prototype utilizes a temperature sensor on the heater head; fuel and air flows are controlled to keep the heater head temperature constant and coordinated together to meet burner combustion requirements.

The United Stirling group is using a control system based in changing the inert, or "dead," volume of the working gas system. An increase in dead volume means that, for a given mean pressure, the pressure decrease due to a given volumetric expansion is lower, as is the work output. This form of power control is thus "pressure amplitude" control as compared to Philips' "mean pressure" control. United Stirling claims adequate responsiveness for the system without any significant efficiency losses. The M.A.N.-MWM group is working on control system which apparently involves mean pressure control with a bypass carefully controlled as a function of crank angle; it is proprietary but they claim good response and high efficiency.

Each of these control concepts is expensive due to complicated valving, piping, chambers, pumps, etc. However: the control system problem seems to be amenable both to new and continued efforts on these concepts, for simplification and consequent cost reduction without a significant sacrifice in efficiency.

An advanced power control and drive system concept now being examined by Philips is the variable-angle swashplate drive. Varying the angle at which the swashplate is connected to the driveshaft changes the swept volume, and effectively changes the dead volume, providing for power output changes without the increase in total working gas volume associated with the explicit use of dead volume. A rudimentary variable-angle swashplate drive system has been tested at Philips, but this must be considered an advanced concept, lagging well behind the more practical control and drive systems discussed above.

A.2.2.3 Working Gas Seals

High pressure hydrogen is notoriously difficult to contain in any system. In the Stirling Engine the most critical point of leakage is where the piston rod slides against the cylinder base. Philips has developed, and is using in the Ford program, the roll-sock seal. This is a rubber diaphragm attached to both the rod and base, sealed with oil on the outer side and providing a hermetic seal. A major open issue is the durability of the roll-sock seal under vehicle operating conditions; it has held up successfully under laboratory conditions and in the Stirling cycle refrigerators sold by Philips. United Stirling is using a much simpler sliding seal arrangement, which they feel can be engineered to contain the gas to the point where a minimal level of make-up will be required.

The high pressure hydrogen also has the ability to diffuse right through the metal walls of cylinder, heater, etc. Philips claims that this problem has been virtually eliminated by the development of a new coating.

Again, however, serious testing remains. Even without the new coating, and even with the use of sliding seals, it appears that the total amount of hydrogen make-up can probably be held to a point where recharge would occur within maintenance periods typically expected of passenger cars. In summary, then, solutions to the problem of containing the high pressure hydrogen seem to be relatively well in hand, at least at the laboratory engine stage. Again, of course, much practical development remains to be accomplished - for example much effort is presently being expended on developing the optimal material for the roll-sock.

A.2.2.4 Other Components

The heater head, power control and seals are presently the individual components receiving the most development effort. The other key components are at, or are likely to shortly be at, the stage where they can be confidently installed in a prototype engine which has completed its Initial Development Stage, i.e. they will demonstrate the necessary performance. These components are the burner, radiator, preheater, regenerator, and cooler.

Stirling engine burners have been shown to sustain combustion with good combustion efficiency and, in simulations of the EPA regulatory driving cycle (the "FDC"), meet the statutory (original 1976) emissions standards for intermediate-size cars when running on gasoline. There is little doubt that they can be designed to achieve high combustion efficiencies in heavier, cheaper, fuels although the emissions issue under those conditions is less clear, both in terms of the regulated pollutants and particulates (and possibly sulfur oxides and odor as well).

The radiator for the Stirling engine needs to be considerably larger than on an ICE-powered vehicle, making it more costly and difficult to package. Neither presently appears to be a major problem; in any case Philips claims to have made a significant advance in radiator design, although the cost aspects of their system are unclear.

Preheaters of two types are presently being used in laboratory engines: stationary "recuperators," where the incoming air flows on one side of a set of passages and the hot exhaust gases on the other, and rotary systems, where the incoming air flows through one side of a rotating disc (probably a ceramic) and the exhaust gases on the other. The Ford-Philips and

United Stirling teams are leaning toward the rotary ceramic system. It is very similar in concept to the preheater used by Ford on automotive gas turbines except that it does not have sealing problems which are as difficult. Automotive gas turbine preheater ceramic discs have had difficulties standing up to the attack of impurities in air and in the combustion products from the fuel; most of these problems seem to have been resolved. The M.A.N.-MWM Group feels they have developed a potentially satisfactory recuperator. In both cases adequate performance is highly likely but cost remains an open issue.

The Stirling engine regenerator, as developed at Philips, consists of a volume of fine steel mesh; it is remarkably efficient; again cost is open.

The cooler on the Stirling engine, where heat is rejected from the engine proper to the cooling water, needs, like the heater head, a system of fine tubes which must contain the high pressure hydrogen while conducting large amounts of heat. The crucial difference is that it does all this at much lower temperatures and therefore, superalloys (or ceramics) are not required; a difficult manufacturing problem remains, however.

Finally, it should be noted that Ford considers it likely that a two-speed accessory drive will have to be developed for use in the engine.

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