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Advanced Vehicle Systems Assessment

Volume IV: Supporting Analyses

Part One: Preference Analyses

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Part Two: Aftermarket Analyses

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16. Abstract

Volume IV (Supporting Analyses) is part of a five-volume report, Advanced Vehicle Systems Assessment. Other volumes are the Executive Summary (Vol. I), Subsystems Assessment (Vol. II), Systems Assessment (Vol. III), and Appendices (Vol. V).

Thirty-nine individuals, knowledgeable in advanced automotive technology, were interviewed to obtain their preferences. Rankings were calculated for the eight groups they represented, using multiplicative and additive utility models.

The rankings were designed to answer four questions: (1) What is the most preferred range for each battery technology - 100, 150, or 250 miles? (2) What are the most promising technologies for each range? (3) What are the most promising battery electric vehicle technology/range combinations? and (4) How do the most preferred of the electric vehicles compare with the methanol-fueled, spark-ignition engine vehicle and with the most preferred of the hybrid vehicles?

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ABSTRACT

Part One of this volume describes the ranking of 34 alternative five-passenger advanced vehicles, using multiattribute decision analysis. The vehicles were designed to operate without consuming any petroleum-based fuels and to have an unrefueled range of 100, 150, or 250 miles. The vehicle propulsion systems included a methanol-fueled spark-ignition engine, a fuel cell, ten different types of batteries in an all-electric configuration, and five different battery types in hybrid configurations with a methanol-fueled engine. Seven attributes affected the rankings: initial cost, life-cycle cost, maintainability, safety, unrefueled range, relative fuel economy, and refuel time.

Thirty-nine individuals, knowledgeable in advanced automotive technology, were interviewed to obtain their preferences. Rankings were calculated for the eight groups they represented, using multiplicative and additive utility models.

The rankings were designed to answer four questions: (1) What is the most preferred range for each battery technology--100, 150, or 250 miles? (2) What are the most promising technologies for each range? (3) What are the most promising battery electric vehicle technology/range combinations? (4) How do the most preferred of the electric vehicles compare with the methanol-fueled, spark-ignition engine vehicle and with the most preferred of the hybrid vehicles?

Part Two of this volume deals with an investigation of the availability of fuel from nonpetroleum sources of fuel from nonpetroleum sources in view of projected supply, demand, and prices in the 1990s.

Volume IV (Supporting Analyses) is part of a five-volume report, Advanced Vehicle Systems Assessment. Other volumes are the Executive Summary (Vol. I), Subsystems Assessment (Vol. II), Systems Assessment (Vol. III), and Appendices (Vol. V).

FOREWORD

The Electric and Hybrid Vehicle (EHV) Division of the U.S. Department of Energy established the Advanced Vehicle (AV) Development Project to assess the potential of nonpetroleum passenger vehicles that fully competed with conventional petroleum-fueled heat-engine vehicles in the 1990s. The Jet Propulsion Laboratory, in its role as the EHV Systems R&D Project Office, was given the AV Assessment Task to provide the technical foundation and make recommendations for research in support of nonpetroleum electric or hybrid vehicles from a systems perspective. Therefore, the objectives of the assessment are to characterize and give priority to the various subsystem technologies and system concepts through the use of vehicle simulation, based on projections of the subsystem capabilities in the next 10 years.

The complete report, Advanced Vehicle Systems Assessment, is divided into five volumes: Executive Summary (Vol. I), Subsystems Assessment (Vol. II), Systems Assessment (Vol. III), Supporting Analyses (Vol. IV), and Appendices (Vol. V).

Part One of Volume IV, Supporting Analyses, describes the ranking of 34 five-passenger AV systems designed for a 100-, 150-, or 250-mile range, using the preferences of 39 individuals knowledgeable in AV technology. Part Two of Volume IV, Aftermarket Analyses, primarily addresses the availability of methanol from various sources and electricity supply.

ACKNOWLEDGMENTS

This report could not have been completed without the support of many individuals who gave generously of their time. The authors thank Keith Hardy, John Langendoen, and Jim Long from the Jet Propulsion Laboratory; and Jerry Walker and Bob Kirk from the U.S. Department of Energy. Considerable thanks are due to those individuals who were interviewed to ascertain their preferences for the attributes for advanced vehicles. Those organizations whose representatives consented to have their organization acknowledged are:

Organization	Location
American Automobile Association	Falls Church, Virginia
BKM	San Diego, California
Bank of America	San Francisco, California
California Energy Commission	Sacramento, California
Conoco Coal Development Company	Stamford, Connecticut
Consumer Reports	Orange, Connecticut
Detroit Edison	Detroit, Michigan
Electric Power Research Institute	Palo Alto, California
Energy Transition Corporation	Santa Fe, New Mexico
Future Fuels of America	Sepulveda, California
GMC Truck and Coach Div. of General Motors	Pontiac, Michigan
GTE Service Corporation	Stamford, Connecticut
General Motors Research Laboratories	Warren, Michigan
Long Island Lighting Company	Minneola, New York
Philadelphia Electric Company	Philadelphia, Pennsylvania
J. D. Power and Associates	Westlake Village, California
Southern California Edison Company	Rosemead, California

Special thanks are owed to Fran Mulvehill, who typed this manuscript with its many difficult tables, and to Thomas S. Lee, who prepared the numerous rankings.

Notwithstanding the help of those persons acknowledged above, the responsibility for this report rests with the authors.

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Part One
Preference Analyses

A. Feinberg
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EXECUTIVE SUMMARY

Thirty-four alternative five-passenger advanced vehicles were ranked using multiattribute decision analysis. The vehicles were designed to operate without consuming any petroleum-based fuels and to have a 30-second maximum start-up time with an unrefueled range of 100, 150, or 250 miles. The vehicle propulsion systems included a methanol-fueled spark ignition engine, a solid polymer electrolyte fuel cell, ten types of batteries in an all-electric configuration, and five battery types in hybrid configurations with a methanol-fueled engine.

Seven attributes affected the rankings: initial cost, life-cycle cost, maintainability, safety, unrefueled range, relative fuel economy, and refuel time. The first five of these attributes most affected the rankings.

Thirty-nine individuals, knowledgeable in advanced automotive technology, were interviewed to obtain their preferences. Rankings were calculated for the eight groups that they represented, using both multiplicative and additive utility models. These rankings were usually consistent from group to group and for the two utility models.

The rankings were designed primarily to answer four questions: (1) What is the most-preferred range for each battery technology--100, 150, or 250 miles? (2) What are the most promising technologies for each range? (3) What are the most promising battery electric vehicle technology/range combinations? (4) How do the most preferred of the electric vehicles compare with the methanol-fueled spark ignition engine vehicle and with the most preferred of the hybrid vehicles?

With only a few exceptions, this study makes the following assertions:

(1) Vehicles with a 250-mile range are preferred to 100-mile-range vehicles, which are in turn preferred to 150-mile-range vehicles.

(2) Top-ranked electric vehicle battery technologies are bipolar, lead-acid, nickel-zinc, lithium-iron sulfide, nickel-iron, and sodium-sulfur, respectively, and top-ranked hybrid vehicle technologies are bipolar, lead-acid, and nickel-zinc.

(3) Top-ranked electric vehicles are the bipolar and lead-acid 100-mile range, the nickel-zinc 100- and 150-mile range, and the lithium-iron sulfide, sodium-sulfur, and nickel-iron 250-mile range.

(4) The top-ranked electric vehicles still rank below the methanol-fueled spark ignition engine vehicle and the top-ranked hybrid vehicles.

The key attributes causing the top-ranked electric vehicles to trail the others are maximum refuel time and unrefueled range. In this study, consistently low-ranked battery technologies were zinc-chlorine and zinc-bromine, both with low safety ratings; and aluminum-air, with high costs.

SECTION I

INTRODUCTION AND SUMMARY

A. INTRODUCTION

Thirty-four alternative five-passenger advanced vehicles (AVs) were studied and ranked, using multiattribute decision analysis. The vehicles were designed to have unrefueled ranges of 100 to 250 miles (160 to 400 kilometers) and to operate without consuming any petroleum-based fuels. The vehicle propulsion systems included a methanol-fueled, spark-ignition engine, a solid polymer electrolyte fuel cell, ten different types of batteries in an all-electric configuration, and five different battery types in hybrid configurations with a methanol-fueled engine.

The issue of unrefueled range is significant in this study. Originally, it was believed that electric vehicles (EVs) would have to possess unrefueled range comparable to present vehicles in order to compete. Thus, in a prior study (Reference 1), EVs with 250-mile unrefueled range were ranked against hybrid vehicles and a vehicle with a methanol-fueled, spark-ignition engine. However, the 250-mile-range EVs had high initial cost and ranked below the hybrid and methanol-fueled vehicles. It was then suggested that the 250-mile-range requirement be relaxed for the electric vehicles to see if shorter-range EVs would rank more favorably. This study is addressed to that question.

Eight attributes were intended to be used in the ranking, but one was fixed for all vehicles - maximum start-up time fixed at 30 seconds (a perceived requirement) so that only seven attributes affected the rankings: relative fuel economy, initial cost, life-cycle cost, maintainability, safety, unrefueled range, and refuel time. The attributes affecting the rankings most were safety, maintainability, cost attributes of initial cost, life-cycle cost, and unrefueled range.

The methodology used to rank the vehicles was multiattribute decision analysis with the base case model using a multiplicative multiattribute utility function (Reference 2). A linear multiattribute utility function was also used to compare with rankings derived from the base case model. The methodology combines an individual's preferences with analytical estimates of the attribute states to produce a ranking for that individual. A flow diagram for the method is shown in Figure 1-1.

Because numerous individuals are involved in a major decision such as the choice of an identification system, the rankings had to be determined for groups as well as for individuals. Thus, Section II (Methodology) includes a discussion of group-decision rules. Three group-decision rules were used to aggregate individual rankings because there is no definitive rule for groups: the rank sum (or Borda), the additive utility, and the Nash bargaining rules.

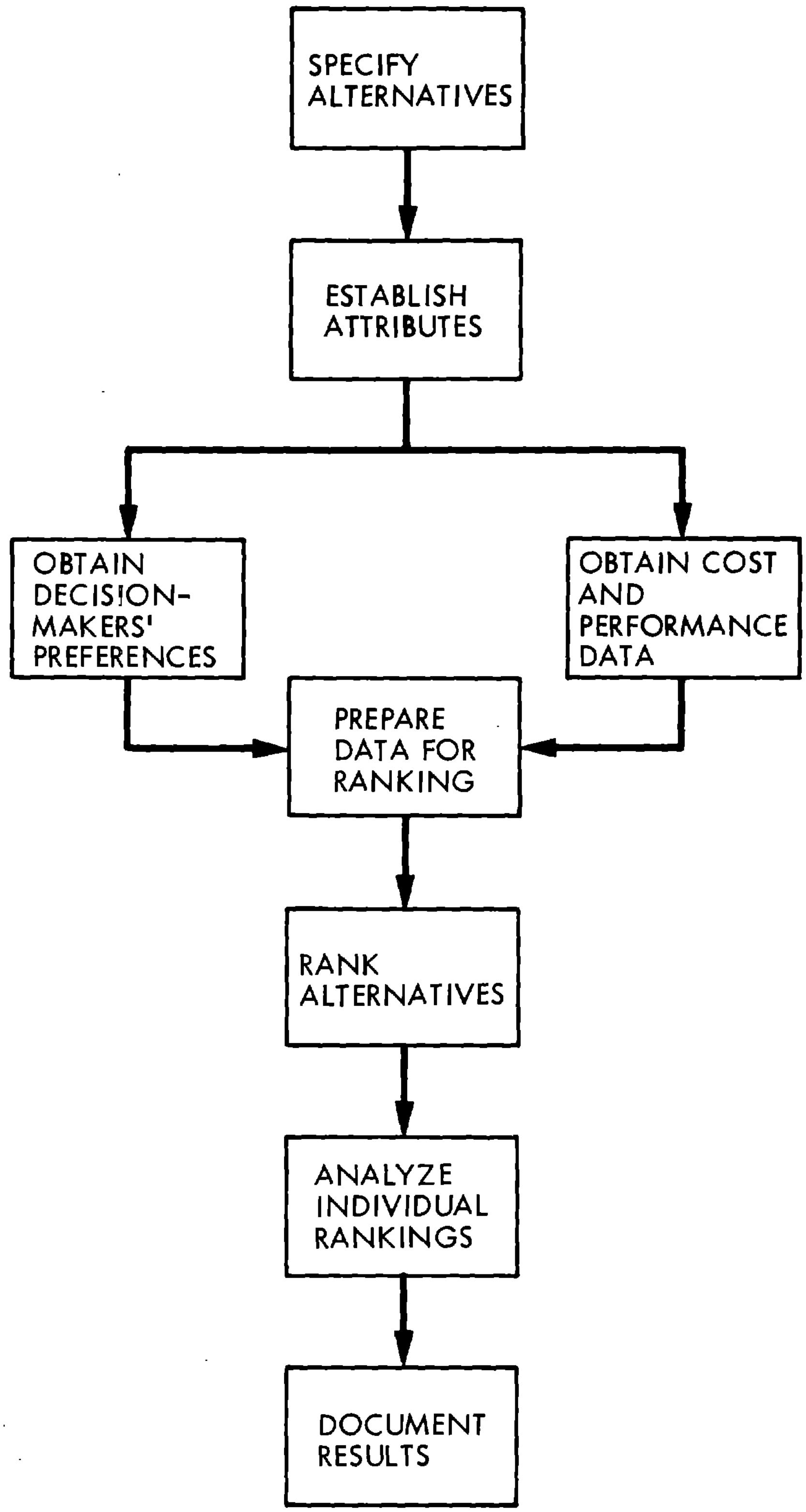


Figure 1-1. Ranking Methodology

B. INTERVIEWS

Thirty-nine individuals, knowledgeable in advanced automotive technology, were successfully interviewed to obtain their preferences with regard to the eight attributes originally selected. These individuals were drawn from organizations with:

(1) Advanced vehicle fleet involvement either in fleet purchasing or management.

(2) Automobile manufacturing advanced vehicle research within a major automobile manufacturing company.

(3) Automobile manufacturing corporate decision-makers with interests in advanced vehicles.

(4) Consumer, professional, and market-analysis organizations with an interest in advanced vehicles.

(5) Fuel suppliers to advanced vehicle markets.

(6) Research organizations conducting research in the advanced vehicle area for utility companies.

(7) Utility companies with an interest in advanced vehicles.

In addition, five interviews were conducted with U.S. Department of Energy (DOE) and Jet Propulsion Laboratory (JPL) personnel.

C. RANKINGS

Rankings were calculated for the 39 individuals successfully interviewed and for the eight groups that they represented. Rankings for the individuals were calculated using several different multiattribute utility models. Rankings for the groups were calculated using three different group-decision rules.

The advanced vehicle technologies evaluated and ranked include a baseline methanol-fueled internal-combustion engine (ICE), a fuel-cell vehicle, an aluminum-air electric vehicle, and both hybrid vehicles (HVs) and EVs for lead-acid, bipolar lead-acid (hereafter called bipolar), nickel-iron, nickel-zinc, zinc-bromine, zinc-chlorine, iron-air, lithium-iron sulfide, and sodium-sulfur battery systems. Vehicle designs for 100- and 150-mile ranges were assessed for all EVs except aluminum-air. EV designs with a 250-mile range were assessed for zinc-chlorine, iron-air, lithium-iron sulfide, sodium-sulfur, and aluminum-air battery systems only. The fuel-cell and hybrid vehicles were all designed for a 250-mile range. The baseline methanol ICE vehicle was designed for a 250-mile range but evaluated over 100-, 150-, 250-mile-range driving cycles to compare with vehicles of each range.

Rankings were calculated for individuals and the eight groups for both multiplicative and additive utility models. The multiplicative model was used for its theoretical rigor and the additive model for its ease of understanding. The ranking results were consistent for both utility function models as well as from group to group.

A series of rankings was carried out to answer a number of questions: (1) What is the most preferred range for each battery technology: 100, 150, or 250 miles? (2) What is the most promising technology for each range: 100, 150, or 250 miles? (3) What are the most promising battery EV technology/range combinations? (4) How do the most preferred of the EVs compare with the baseline ICE and most preferred of the HVs?

In response to the first question of range preference, the 250-mile-range HVs are most preferred, followed by 250-mile-range EVs (when available), with 100-mile-range EVs next, and 150-mile-range EVs least preferred. There are two exceptions. The nickel-zinc 100- and 150-mile-range EVs are about even in the rankings, and electric utility representatives interviewed preferred 150-mile-range vehicles to 100-mile-range vehicles.

For 100- and 150-mile-range EVs and the baseline ICE, top-ranked technologies are bipolar, baseline, lead-acid, nickel-zinc, and lithium-iron sulfide. Next are nickel-iron, sodium-sulfur, and iron-air with zinc-chlorine and zinc-bromine ranked lowest. For 250-mile-range EVs, the baseline ICE, and a fuel-cell-powered vehicle, rankings indicate that the baseline ICE is most preferred; fuel-cell and lithium-iron sulfide next (equally ranked); followed by sodium-sulfur, iron-air, aluminum-air, and zinc-chlorine, respectively. Rankings for the baseline ICE and 250-mile-range HVs are similar to the rankings for 100- and 150-mile EV technologies.

The ranking designed to ascertain the most promising battery EV technology/range combinations indicated that the bipolar 100-mile-range vehicle is most preferred, the lead-acid 100-mile range vehicle ranks next, with nickel-zinc 100- and 150-mile-range vehicles following. These four technolgies rank higher than the six highest-ranked 250-mile-range EVs, led by lithium-iron sulfide; sodium-sulfur and nickel-iron (equally ranked); followed by iron-air, zinc-chlorine, and zinc bromine 250-mile-range EVs.

Rankings for the most-preferred 250-mile-range vehicles show the bipolar HV as highest-ranked; the lead-acid HV, the baseline ICE, and nickel-zinc HV next; followed by the lithium-iron sulfide HV, nickel-iron HV, fuel-cell, lithium-iron sulfide EV, sodium-sulfur EV and iron-air EV, respectively. At the 250-mile range, the baseline ICE and most-preferred HVs rank before the most-preferred EVs.

The final ranking addressed the question of whether the most-preferred EVs, regardless of range, would compete with the baseline and most-preferred of the HVs. Because of long refuel time and shorter unrefueled range, the EVs do not compete because the bipolar HV, baseline ICE, lead-acid HV, and nickel-zinc HV are all preferred to the most-preferred of the EVs (the bipolar EV with 100-mile-range). The bipolar 100-mile-range EV is preferred to the lithium-iron sulfide HV, lead-acid 100-mile-range EV, nickel-zinc 150-mile-range EV, lithium-iron sulfide 250-mile-range EV, and sodium-sulfur 250-mile-range EV, in that order.

D. CONCLUSIONS

The top-ranked EVs still rank below the baseline ICE and the top-ranked HVs.

The key attributes causing top-ranked EVs to be less preferred to the baseline ICE and top-ranked HVs are maximum refuel time (8 hours for all EVs except aluminum-air) and unrefueled range.

Top-ranked EV battery technologies are bipolar, lead-acid, nickel-zinc, lithium-iron sulfide, nickel-iron and sodium-sulfur, respectively. Top-ranked HV technologies are bipolar, lead-acid, and nickel-zinc.

Consistently low-ranked battery technologies are zinc-chlorine and zinc-bromine (both have low safety ratings) and aluminum-air (high cost).

E. REPORT STRUCTURE

This report is divided into six sections: Introduction and Summary (Section I); Methodology (Section II); Objectives, Criteria, and Attributes (Section III); Alternatives and Attribute-State Data (Section IV); Interviews (Section V); and Analysis and Discussion of Rankings (Section VI).

SECTION II

METHODOLOGY

This section describes and illustrates the general methodology used to evaluate and compare alternative advanced vehicles. The methodology consists of a number of steps that characterize the alternative approaches under different design options and operating environments, assign utility values to the alternatives, and rank the alternatives based on these utilities. The actual application reported here does not include the assessment of probabilities, but the methodological coverage is included for completeness.

The general evaluation methodology may be summarized as follows. The process begins with the selection of a set of descriptive but quantifiable attributes designed to characterize each vehicle. Values for this set of attributes then are generated for each alternate approach that specify its response (e.g., performance or cost) under different design options and operating environments. (The attributes are discussed in Section III.) A decision tree can be constructed to relate economic, technological, and environmental uncertainties (i.e., the operating environment) to the cost and performance outcomes (i.e., attribute values) of the alternative vehicles. Multiattribute utility functions that reflect the preferences and perceptions of knowledgeable individuals are generated, based on interviews with selected personnel. The functions are then used to generate a multiattribute utility value for each system, based on its characteristics under the scenarios reflected within the decision tree. The decision tree is used to compute an expected multiattribute utility value for each alternative, the expected value being taken over the scenario probability distribution. Alternative systems are ranked according to this expected multiattribute utility value.

A. MULTIATTRIBUTE DECISION ANALYSIS

1. Overview

Multiattribute decision analysis is a methodology for providing information to decision-makers for comparing and selecting from among complex alternative systems in the presence of uncertainty. The methodology of multiattribute decision analysis is derived from the techniques of operations research, statistics, economics, mathematics, and psychology. Thus, researchers from a wide range of disciplines have participated in the development of multiattribute decision analysis. The first books and papers on the subject appeared in the late 1960s (References 3 through 6). The most practical, extensive, and complete presentation of an approach to multiattribute decision analysis is given in the 1976 work of Keeney and Raiffa (see Reference 2). Although a number of approaches to multiattribute decision analysis have been developed (References 7 through 19), the method used in this report corresponds to an abbreviated form of the Keeney and Raiffa report. A brief introduction to multiattribute decision analysis, discussing primarily the Keeney and Raiffa methodology, is given by Feinberg and Miles (Reference 20). The assumptions needed for the abbreviated form used here are discussed at the end of Section II-A-5 of this report.

Every systems analysis involving the preference ranking of alternative systems, whatever the specific methodology, requires two kinds of models. One is a "system model" and is representative of the alternative systems (including any uncertainties) under consideration. The other is a "value model" and is representative of the preference structure of the decision-makers whose preferences are being assessed.

The system model describes the alternative systems available to the decision-makers in terms of the risk and possible outcomes that could result from each. Risk arises from the technological and economic uncertainty associated with each alternative system and from the uncertain environment in which the systems would be required to perform. The outcomes describe the possible consequences of the alternative systems. Because of the element of risk, the selection of a specific system does not in general guarantee a specific outcome, but rather results in a probabilistic situation in which only one of several outcomes may occur. These outcomes, with their measurable attributes, then form the input to the value model. The value model assesses the outcomes in terms of the preferences of the decision-makers for the various outcomes. The measurable attributes of the outcomes are aggregated algebraically in a formula (called a multiattribute utility function) whose functional form and parameters are determined by the preference structure of the decision-makers. The output of the value model is a multiattribute utility function value for each outcome (outcome utility). These outcome utilities are entered back into the system model where an alternative system utility can be calculated for each alternative system simply by taking the expected utility value of the outcomes associated with each alternative system. These alternative system utilities then define a preference ranking over the alternative systems, with greater alternative system utilities being more preferred.

The relationship between the system model and the value model is illustrated in Figure 2-1, which shows that the combination of a selected system and a realized state of uncertainty results in the output from the system model to the value model of a specific outcome. The output of the value model is an outcome utility. The probabilistic combination of the outcome utilities of the outcomes associated with a specific alternative system determine an alternative system utility in the system model. Comparison of the alternative system utilities for all the alternative systems under consideration results in a alternative system ranking as the output from the system model.

2. Decision Trees

Decision trees are used to represent the system model and the inputs to the system model at the gross level required for the decision analysis. Decision trees are graphically depicted by decision nodes (represented by squares), with alternative paths emanating from them; and by chance nodes (represented by circles), with probabilistic paths emanating from them. All paths either terminate at another node or terminate at an outcome, which is a description of the consequence of traversing a specific set of paths and nodes through the decison tree from beginning to end. There can be only one originating node (either a decision node or a chance node). There can be many outcomes terminating the decision tree, depending on the complexity of the decision tree.

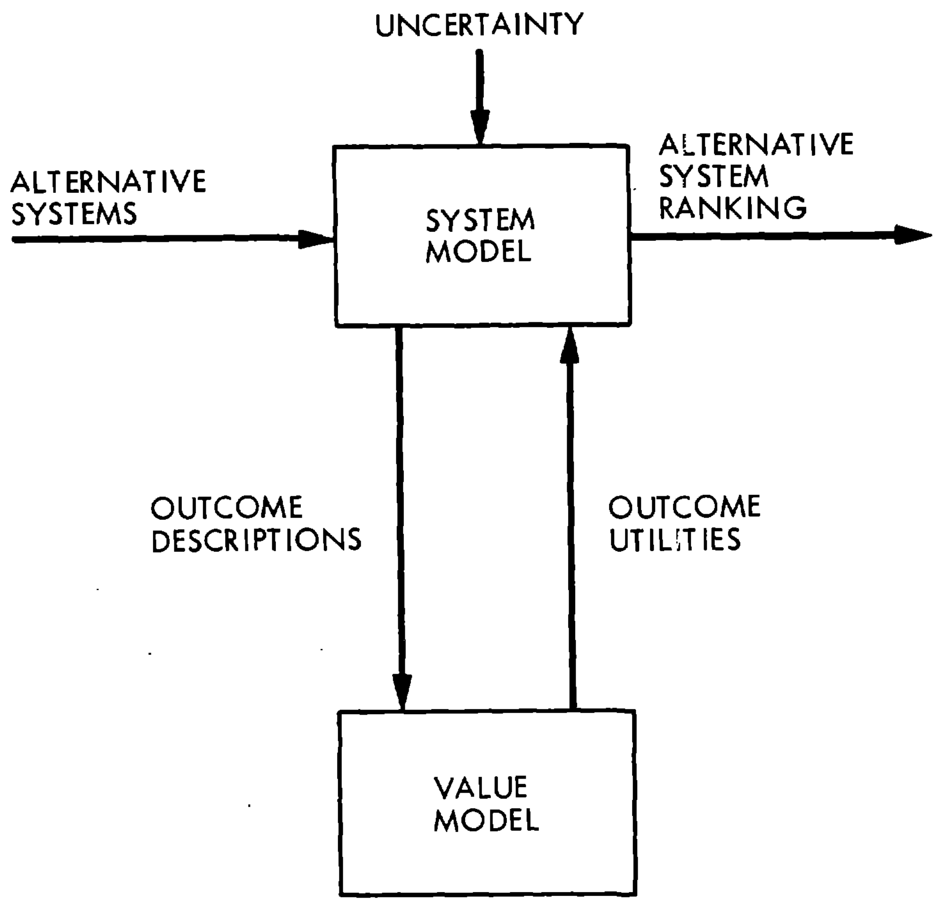


Figure 2-1. Relationship Between System Value Models

Figure 2-2 shows a typical decision tree, terminating in 10 outcomes. The symbols "D_i" stand for the ith decision node ("D" for decision). The symbols "P_j" stand for the jth chance node ("P" for probabilistic). The symbols "C_k" stand for the kth outcome ("C" for consequence). Every path emanating from a decision node corresponds to an alternative that the decision-makers can select, where "$A_{i\ell}$" stands for the ℓth alternative selected at the ith decision node. The decision-makers can select one and only one path at each decision node. Every path P_{jm} emanating from a chance node corresponds to one of the uncertain and uncontrollable chance states that can occur at that node, where p_{jm} is the probability that the mth chance state will be realized at the jth chance node. The p_{jm}s must obey the laws of probability theory. Thus, one and only one chance path can be realized from a chance node and the p_{jm}s must sum to 1.0.

The chance nodes and their associated chance paths and probabilities are called "gambles" or "lotteries" in the literature. This report shall refer to them as gambles. An example of a gamble would be a flip of a coin, which could be expected to come up heads 50% of the time and tails 50% of the time. Graphically, such a gamble would be displayed as:

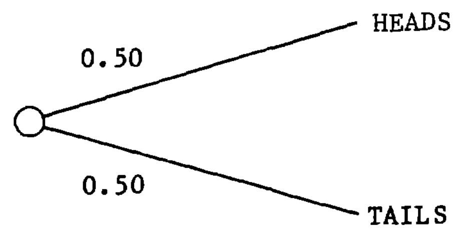


Figure 2-2 has an example of every kind of node-path-outcome relationship. There are examples of decision-node to decision-node paths, decision-node to chance-node paths, decision-node to outcome paths, chance-node to decision-node paths, chance-node to chance-node paths, and chance-node to outcome paths.

As an example of how the decision tree might be traversed, imagine that the decision-maker selects Alternative Path A_{12} at Decision Node D_1, where he must start. This leads to Chance Node P_1 where Chance Path P_{13} is realized, leading to Chance Node P_3, where Chance Path P_{32} is realized, and terminates with Outcome C_{10}.

3. Determination of Probabilities

The decision trees have probabilities associated with all of the chance paths. These probabilities need to be assessed as perceived by the decision-makers or as perceived by experts whose judgment the decision-makers would be willing to accept.

Two conditions must be satisfied by the probabilities associated with the chance paths emanating from the single-chance node. The probabilities must be "coherent" and "veridical" (Reference 21). To be "coherent" means that the probabilities obey the laws of probability theory. This requires that the chance paths emanating from a single-chance node correspond to probability events that are mutually exclusive and collectively exhaustive (one and only one of the chance paths must occur) and that the probabilities assigned to all the chance paths emanating from a single-chance node must be non-negative and sum to 1.0. To be "veridical" means that the probabilities must bear some correspondence to reality. For example, if the probability 1/n were assigned to the "n" chance paths emanating from a chance node, coherence would be satisfied if the chance paths corresponded to mutually exclusive and collectively exhaustive events because these probabilities sum to 1.0. However, veridicality would be violated if one of the chance paths was perceived as being very improbable because the assignment of a probability of 1/n to that chance path would be inappropriate.

An excellent review and an extensive bibliography on the assessment of probabilities is given by Hogarth (Reference 22). The philosophy and practice used in probability assessment by the Decision Analysis Group at SRI, International is given by Spetzler and Stael Von Holstein (Reference 23).

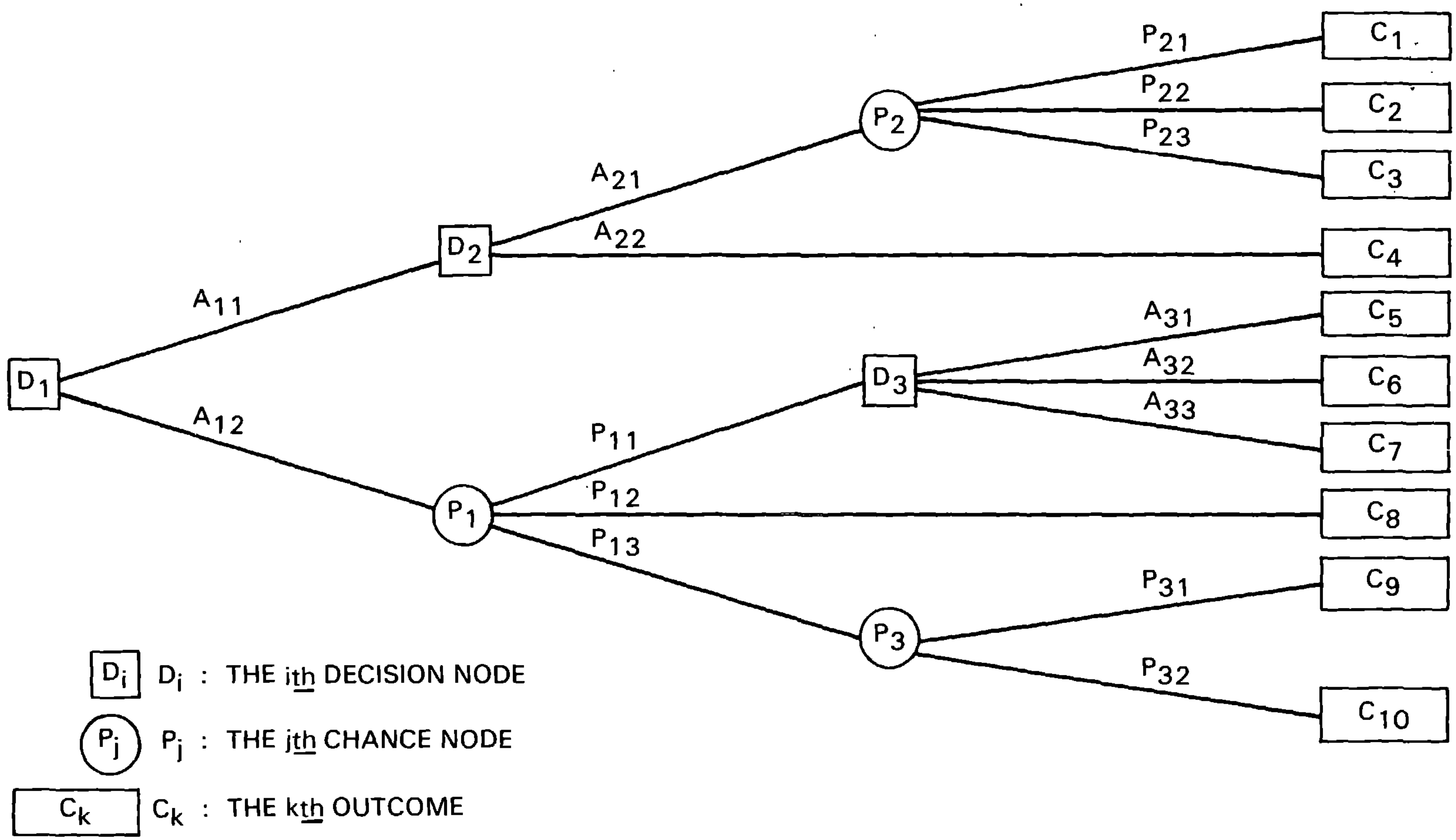


Figure 2-2. Typical Decision Tree

Elementary discussions of probability assessment are given in Keeney and Raiffa; Schlaifer; and Brown, Kahr, and Peterson (see References 2, 6 and 21, respectively) and Winkler (Reference 24). The probability assessment technique presented in this report attempts to satisfy the requirements of coherence and veridicality with a minimum of effort on the part of the assessor and the decision-makers or experts whose subjective probabilities are being assessed.

The probability assessment technique first involves the construction of chance paths satisfying the mutually exclusive and collectively exhaustive condition. In Figure 2-2, three chance paths (P_{11}, P_{12}, and P_{13}) emanate from Chance Node P_1. These three chance paths might, for example, correspond to the events: (1) For Chance Path P_{11}, Alternative System A_{12} costs $25,000 or less, with a most-probable cost of $15,000 and performs as specified; (2) for Chance Path P_{12}, Alternative System A_{12} costs more than $12,000 with a most-probable cost of $18,000 and performs as specified; and (3) for Chance Path P_{13}, Alternative System A_{12} has a most-probable cost of $10,000 but does not perform well enough to be used. Rigorously, according to decision-analysis theory, "certainty equivalent" costs (see Reference 2) should be used rather than "most-probable" costs as in the preceding statements, but for this discussion "most probable" will suffice.

The next step is to assess probabilities to be assigned to each of the chance paths. This is done by interviewing either the decision-makers or their designated experts according to the following format:

(1) Ask the interviewee to rank the chance paths emanating from a chance node in order of decreasing perceived probability of occurrence.

(2) For the chance node, ask the interviewee, "How much more probable is the most-probable chance path than the least-probable chance path? A little? Ten times? A hundred times?

(3) If the reply is a number, such as "six times more probable," then consider the next least-probable chance path.

(4) If the reply is "a little," then ask, "Is the most-probable chance path 10%, 25% or 50% more probable?" The interviewee should respond with whatever percentage he feels is appropriate. Then consider the next least-probable chance path.

(5) Repeat (2) to (4) for all of the chance paths of the chance node.

(6) Repeat (1) to (5) for all of the chance nodes relevant to the interview.

This is all the information that is required from the interview for assessing probabilities for the chance paths. The probabilities for the chance paths can be calculated from the interview responses by solving a set of simultaneous equations of the form

$$p_{jm^*} = x_{jm'} \, p_{jm'}$$

where "p_{jm*}" is the probability associated with the most-probable chance path, "$p_{jm'}$" is the probability associated with some other path, and where "$x_{jm'}$" is the response. The p_{jm}s are subject to the condition

$$\sum_{m=1}^{M} p_{jm} = 1.0$$

In the preceding example, suppose that the responses given were that p_{11} was ten times as probable as p_{13}, but p_{11} was only 25% more probable than p_{12}. The equations to solve would be:

$$p_{11} = 10p_{13}$$

$$p_{11} = 1.25p_{12}$$

$$p_{11} + p_{12} + p_{13} = 1.0$$

The solution is

$$p_{11} = 0.526;\ p_{12} = 0.421;\ p_{13} = 0.053$$

4. Objectives Hierarchy

The outcomes that terminate the decision tree are to be described in terms of an objectives hierarchy that (1) expresses the preference structure of the decision-makers, and (2) is constructed in a manner compatible with the quantification and mathematical conditions required by a multiattribute utility function of the value model. The objectives hierarchy expresses the preference structure of the decision-makers in ever increasing detail as one proceeds down through the hierarchy from overall objective to a lower-level hierarchy of subobjectives. Below the subobjectives are "criteria." The criteria must permit the quantification of performance of the alternatives with respect to the subobjectives. Associated with each criterion is an "attribute," a quantity that can be measured and for which the decision-makers can express preferences for its various states. Figure 2-3 shows an objectives hierarchy with the associated attributes.

The set of attributes must satisfy the following requirements for the value model to be a valid representative of the preference structure of the decision-makers:

(1) Completeness: The set of attributes should characterize all of the factors to be considered in the decision-making process.

(2) Comprehensiveness: Each attribute should adequately characterize its associated criterion.

(3) Importance: Each attribute should represent a significant criterion in the decision-making process, at least in the sense that the attribute has the potential for affecting the preference ordering of the alternatives under consideration.

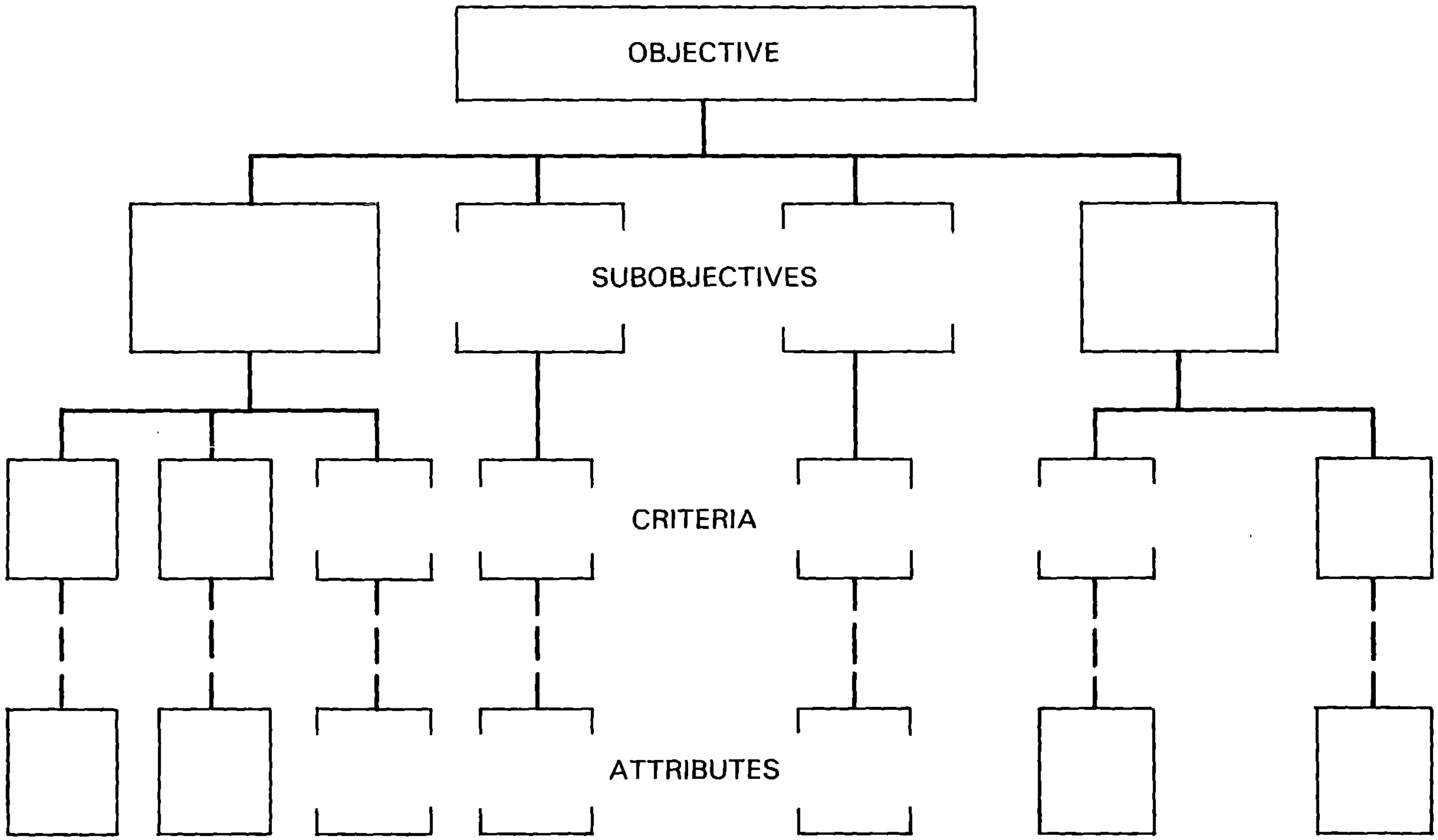


Figure 2-3. Hierarchy of Objectives, Criteria, and Attributes

(4) Measurability: Each attribute should be capable of being objectively or subjectively quantified; technically, this requires that it be possible to establish an attribute utility function for each attribute.

(5) Familiarity: Each attribute should be understandable to the decision-makers in the sense that they should be able to identify preferences for different states of the attribute for gambles over the states of the attribute.

(6) Nonredundancy: Two attributes should not measure the same criterion, thus resulting in double counting.

(7) Independence: The value model should be so structured that changes within certain limits in the state of one attribute should not affect the preference ordering for states of another attribute or the preference ordering for gambles over the states of another attribute.

5. Attribute Utility Functions and the Multiattribute Utility Function

The set of attributes associated with the objectives hierarchy must satisfy the aforementioned measurability and mathematical requirements. If it satisfies these requirements, then it is possible to formulate a mathematical function, called a multiattribute utility function, that will assign numbers, called outcome utilities, to the set of attribute states characterizing an outcome. The multiattribute utility function that was used is that of Keeney and Raiffa (see Reference 2). The outcome utilities generated by the Keeney and Raiffa multiattribute utility function have the properties of Von Neumann and Morgenstern utilities (Reference 25), that is:

(1) Greater outcome utility values correspond to more preferred outcomes.

(2) The utility value to be assigned to a gamble is the expected value of the outcome utilities of the gamble.

The mathematical axioms that must be valid for these two properties to hold were first derived by Von Neumann and Morgenstern (see Reference 25). Elementary expositions of these axioms are given by Hadley (Reference 26) and Luce and Raiffa (Reference 27). An intermediate exposition is given by DeGroot (Reference 28). An advanced exposition is given by Fishburn (Reference 29).

To every outcome "C," an N-dimensional vector of attributes $x = (x_1, \ldots, x_N)$ will be associated, the set of which satisfies the attribute requirements presented in the preceding subsection. Most of the attribute requirements are self-evident. The seventh requirement, that of attribute independence, is a condition that makes it possible to consider preferences between states of a specific attribute, without consideration of the states of the other N-1 attributes. It is thus possible to construct an attribute utility function that is independent of the other attribute states, and which, like the outcome utility function, satisfies the Von Neumann and Morgenstern properties for utility functions. This condition of independence, or some equivalent mathematical condition (see Reference 2 for alternative formulations), is necessary for the Keeney and Raiffa methodology. It is necessary to verify that this condition is valid in practice, or more correctly, to test and identify the bounds of its validity.

To continue the discussion, it is necessary to introduce some mathematical notation:

x_n = state of the n<u>th</u> attribute

x_n^o = least-preferred state to be considered for the n<u>th</u> attribute

x_n^* = most-preferred state to be considered for the n<u>th</u> attribute

x = vector $(x_1, \ldots ,x_N)$ of attribute states characterizing a specific outcome

x^o = *outcome constructed from the least preferred states of all the attributes:* $x^o = (x_1^o, \ldots ,x_N^o)$

x^* = outcome constructed from the most-preferred states of all attributes: $x^* = (x_1^*, \ldots ,x_N^*)$

$(x_n, \bar{x}_n^o)$ = outcome in which all attributes except the n<u>th</u> attribute are at their least-preferred state

$u_n(x_n)$ = attribute utility of the n<u>th</u> attribute

$u(x)$ = outcome utility of the outcome x

k_n = *attribute scaling constant for the* n<u>th</u> *attribute:* $k_n = u(x_n^*, \bar{x}_n^o)$

k = master scaling constant for the multiattribute utility equation. It is an algebraic function of k_n.

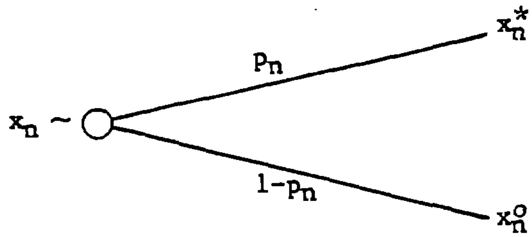
With this mathematical notation, the discussion can proceed to how attribute utility functions and the attribute scaling functions are assessed. The mathematics permit the arbitrary assignments

$$u_n(x_n^o) = 0.0$$

and

$$u_n(x_n^*) = 1.0$$

Thus, the attribute utility function values will range from 0.0 to 1.0. Attribute utility function values for attribute states x_n intermediate between x_n^o and x_n^* are assessed by determining a value of p_n such that the decision-makers or their designated experts are indifferent between receiving x_n for sure <u>or</u> a gamble that yields x_n^o with probability p_n or x_n^* with probability $1-p_n$. Graphically, assess p_n so that



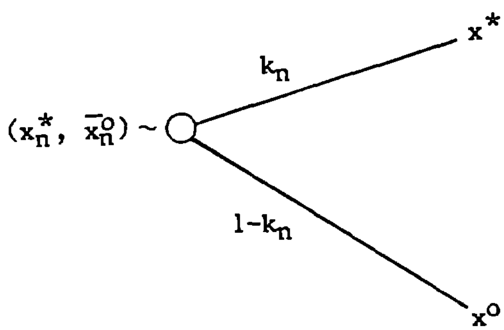
where "~" means indifference.

It follows from the mathematics that

$$u_n(x_n) = p_n$$

This indifference relation is repeated for various attribute states until either a continuous utility function can be approximated or enough discrete points have been assessed for the attribute states under consideration in the analysis.

A similar approach is used to assess the scaling constants k_n. A value for k_n is assessed so that the following indifference relationship holds



With this assessed information, the multiattribute utility equation can be solved to yield an outcome utility value for any outcome under consideration. The multiattribute utility function can now be stated. If

$$\sum_{n=1}^{N} k_n \neq 1.0$$

then

$$u(x) = \frac{1}{k}\left\{\prod_{n=1}^{N}\left[1 + k\,k_n\,u_n(x_n)\right] - 1\right\}$$

where the master scaling constant k is solved for from the equation

$$1 + k = \prod_{n=1}^{N}(1 + k\,k_n)$$

If

$$\sum_{n=1}^{N} k_n = 1.0$$

then there is an additive utility function

$$u(x) = \sum_{n=1}^{N} k_n\,u_n(x_n)$$

The outcome utility function values, like the attribute utility function values, will all range from 0.0 to 1.0 with $u(x^o) = 0.0$ and $u(x^*) = 1.0$. Although the mathematical equations appear complex, they can be easily solved, and the information required in the interviews with the decision-makers can be minimized. An extended discussion of these equations, their solution, and the assessment of the required data, together with examples taken from actual applications, is given by Keeney and Raiffa (see Reference 2).

In this study, an abbreviated form of Keeney and Raiffa's methodology was used to reduce the interview time for the interviewee. An assumption was made that utility independence of each attribute implies pair-wise utility independence (i.e., the attributes exhibit utility independence when taken two at a time). This assumption allows the use of Formulation (4) of Theorem 6.2 of Keeney and Raiffa (see Reference 2). Given single-attribute utility independence, the authors could not construct a realistic example where pair-wise utility independence would be violated.

The abbreviated form satisfies the multilinear model shown in Theorem 6.3 of Keeney and Raiffa. However, the multilinear form requires the assessment of 2^n-2 scaling constants, where n is the number of attributes. With n = 8 attributes, 254 scaling constants would be needed, requiring extensive time for both the interviewer and interviewee.

6. Ranking the Alternative Systems

The steps needed prior to ranking the alternatives are: the development of a decision tree, the determination of probabilities for the decision of an objectives hierarchy, the quantification of the criteria in terms of measurable attributes, and the determination of a multiattribute utility function with attribute utility functions and attribute scaling constants corresponding to the preference structure of the decision-makers. The ranking of the alternative systems proceeds as follows (see Figure 2-2):

(1) Use the multiattribute utility function to calculate outcome utilities for all of the outcomes of the decision tree.

(2) Calculate a utility value to be assigned to all chance nodes by taking the expected utility value of the utilities assigned to the termination of the chance paths of the chance nodes. The chance paths may terminate at outcomes, other chance nodes, decision nodes, or a combination of these.

(3) Calculate a utility value for all decision nodes by selecting the decision path that terminates in an outcome, chance node, or decision node with the highest utility value. The utility value of that path shall be the utility value assigned to the decision node.

The decision tree for this study has an originating decision node whose decision paths correspond to the alternative systems under consideration. Steps (1) through (3) are performed by starting with the outcomes as shown in Figure 2-2 and assigning utility values to these outcomes. Then Steps (2) and (3) are performed by a "folding back" process, proceeding from right to left, and assigning utility values to the chance nodes and the decision nodes. Finally, utility values are assigned to the decision paths emanating from the orginating decision node on the left. These utility values are the ones assigned to the alternative systems. Because greater utility values correspond to more preferred systems, a rank order in preference for the alternative system can be assigned in correspondence with the utility values. A quantifiable and tangible measure of the strength of preference between the alternative systems can be obtained by referencing each alternative system to a set of systems where only one attribute, such as initial cost, is varied (References 30 and 31). The differences in the attribute states of this one attribute varied in order to obtain indifference to each of the alterative systems and will provide a tangible measure of the strength of preference between the alternative systems.

7. Group-Decision Models

Throughout this section, the term "decision-makers" has been consistently discussed in the plural. It is true that in American society, corporate and government (executive branch) decisions are ultimately the responsibility of one person although the same cannot be said for either the legislative branch of government or the voting public. Thus, depending upon the context, it may be more appropriate to speak of decision-maker in the singular. Nevertheless, when one person holds the ultimate responsibility for the decision, this person may elect to delegate the decision-making responsibility to a group, or at least consider the preferences of several others prior to making the decision.

Unfortunately, there presently exist no analytical models for group decision-making that do not violate some intuitively desirable conditions. Arrow (Reference 32) was the first to demonstrate this fact. Extensive discussions of group decision-making can be found in Fishburn (Reference 33), Luce and Raiffa (see Reference 27), and Sen (Reference 34). The best that can be done is to look at a range of group-decision models, and where consensus of the models is found, define that as the consensus of the group (References 35).

The three group-decision rules that are considered in this report are the Borda Rule, the Nash Bargaining Rule, and the Additive Utility Rule. (The Majority Decision Rule, which originally was considered for use in this analysis, was not used because of unsolved theoretical problems that arise when more than two alternatives are involved.)

The Borda Rule (References 32 and 36) or the Rank Sum Rule in the slightly modified form proposed here, requires the calculation of the sum of the ordinal ranks for each alternative, with the alternative receiving the lowest rank sum being most preferred. Young (Reference 37) has stated four axioms that are necessary and sufficient for any collective choice rule to be equivalent to the Borda Rule.

The Nash Bargaining Rule calculates the product of the utilities assigned by all the individuals to an alternative. The alternatives with greater utility product are more preferred, and from this a group preference order can be established. The Nash Bargaining Rule satisfies Nash's four axioms of "fairness" (Reference 38). As the number of decision-makers increases, the Nash utilities decrease because the individual utilities are ≤ 1. Hence, for even ten decision-makers, the Nash utilities are small. Without loss of generality, the Nash utilities can be rescaled by taking the nth root of the product of the individual utilities, where n is the number of decision-makers in the group.

The modern formulation of the Additive Utility Rule is that of Harsanyi (Reference 39). The Additive Utility Rule averages the utility values assigned by the individuals to each alternative, with higher average utility values being more preferred.

It should be re-emphasized that there is no theoretically compelling reason to use the results of any of these group-decision rules, but they do provide information concerning the collective preferences of the decision-makers.

B. RISK ANALYSIS

1. Introduction

Another element of the sensitivity analysis effort is that of risk analysis. Risk is defined as the possibility of loss or injury. This subsection explains and illustrates the elements of risk analysis and describes how risk analysis is incorporated into the multiattribute decision-model and into the sensitivity analysis.

2. Risk-Analysis Elements

Often, the concept of risk analysis is introduced in the context of comparing two alternatives that have equal expected dollar value. An example is the following pair of alternatives:

Option A: $1000 for sure.

Option B: A 50-50 chance of zero dollars or of $2000.

Although both options A and B have equal expected dollar values of $1000, they may not have equal expected utilities for some individuals. An individual's preferences between options A and B reveal his attitude toward risk in the range $0 to $2000:

(1) An individual preferring A to B is characterized as risk-averse.

(2) An individual preferring B to A is characterized as risk-prone.

(3) An individual indifferent between A and B is characterized as risk-neutral.

In the context of advanced vehicle ranking, risk is apparent in the following hypothetical situation:

Option C: Fuel economy of 50 miles per gallon equivalent with an initial cost of $15,000.

Option D: 50-50 chance of 20 miles per gallon equivalent fuel economy or of 80 miles per gallon fuel economy with an initial cost of $15,000.

Although both options C and D have equal expected fuel economy and equal initial costs, individuals may exhibit different preferences, as with the previous dollar example. An individual preferring Option C to Option D is characterized as risk-averse, etc.

Risk attitude implies a certain shape of the individual's utility function and vice versa (see References 2 and 4). A risk-averse attitude for an attribute is equivalent to a concave utility function for that attribute. Also, risk proneness is equivalent to a convex utility function; and finally, risk neutrality is equivalent to a linear utility function. All three of these shapes are shown in Figure 2-4 for an increasing utility function. An increasing utility function exists for an attribute for which the decision-maker prefers higher values to lower values.

The attitude of an individual toward risk varies with the range of outcomes. For example, few of us who would prefer Option B above would give $1,000,000 for sure for a 50-50 chance at zero or $2,000,000. Nevertheless, variation in individual attitude toward risk is evidenced by many motorists who drive from Los Angeles to Las Vegas to gamble (risk-prone), yet carry insurance on their automobiles (risk-averse).

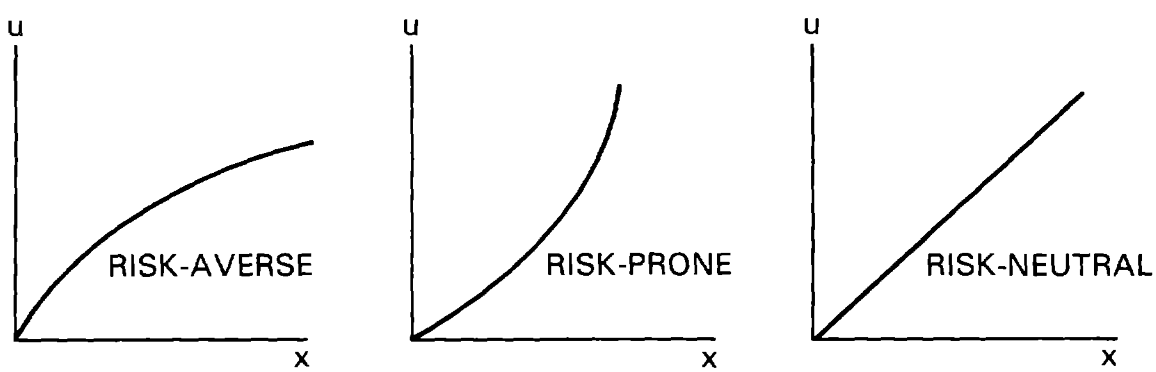
3. Incorporation of Risk in Multiattribute Decision-Making

Risk has usually been incorporated in multiattribute decision-making by taking the individual decision-maker's utility functions and probabilities of various outcomes and combining them to obtain an expected multiattribute utility for each decision alternative. Alternatives can then be ranked in order of expected multiattribute utility with the higher expected utility being the more preferred. The incorporation of risk in such a ranking occurs because the individual's attitude toward risk is embodied in the utility functions used to calculate expected utility. If he is risk-averse, then his multiattribute utility function will yield lower utility values for riskier alternatives. Similarly, if he is risk-prone, riskier alternatives will have higher utility values.

C. CONCORDANCE

It is important to determine the extent of agreement among interviewees as to the ranking of the alternative systems. To this end a statistic known as Kendall's Coefficient of Concordance was employed. This statistic varies between zero and one, with one corresponding to exact agreement among the judges and lower values indicating a greater degree of disagreement. The statistic has a known probability distribution. Thus, tests of significance can be performed.

In the current analysis, the hypothesis that the set of rankings produced by a number of judges are independent was tested. The null hypothesis, if accepted, would imply disagreement among judges. The more decisively one rejects this null hypothesis, the greater is the agreement, or concordance, among the judges.



(x = fuel economy in miles-per-gallon equivalent)

Figure 2-4. Examples of Increasing Utility Functions for Different Risk Attitudes

Kendall's Coefficient of Concordance, W, is given by the following equations

$$W = \frac{S}{\frac{1}{12} k^2(N^3 - N) - k \sum_{i=1}^{k} T_i}$$

where

$$S = \sum_{j=1}^{N} (R_j - \bar{R})^2$$

$$\bar{R} = \frac{1}{N} \sum_{j=1}^{N} R_j = k(N + 1)/2$$

$$T_i = \sum_{j=1}^{N} \left(t_{ij}^3 - t_{ij}\right)/12$$

and

N = number of alternatives

k = number of judges

R_j = sum of the ranks assigned to alternative j

t_{ij} = number of tied observations for rank j and judge i

The ranks, R_j, of tied observations are taken as equal to the average of the ranks they would have been assigned had no ties occurred. For example, suppose five alternatives, a through e, are ranked (from best to worst) d, a, c, e, b, with c and e tied. Ranks would be assigned as follows: d-1, a-2, c-3.5, e-3.5, b-5.

Table 2-1 gives the 5% and 1% significance points for S (the unnormalized statistic) and various values of k and N. When $N \geq 7$ one can use the fact that $k(N - 1)W$ has, approximately, a chi-square distribution with $N - 1$ degrees-of-freedom. When $k(N - 1)W$ exceeds the critical significance point, the null hypothesis of independence of rankings, or lack of concordance among the judges is rejected.

Table 2-1. Table of Critical Values of "S" in the Kendall Coefficient of Concordance[a]

	N					Additional values for N = 3	
k	3	4	5	6	7	k	S
			Values at the 0.05 Level of Significance				
3			64.4	130.9	157.3	9	54.0
4		49.5	88.4	143.3	217.0	12	71.9
5		62.6	112.3	182.4	276.2	14	83.8
6		75.7	136.1	221.4	335.2	16	95.8
8	48.1	101.7	183.7	299.0	453.1	18	107.7
10	60.0	127.8	231.2	376.7	571.0		
15	89.8	192.9	349.8	570.5	864.9		
20	119.7	258.0	468.5	764.4	1158.7		
			Values at the 0.01 Level of Significance				
3			75.6	122.8	185.6	9	75.9
4		61.4	109.3	176.2	265.0	12	103.5
5		80.5	142.8	229.4	343.8	14	121.9
6		99.5	176.1	282.4	422.6	16	140.2
8	66.8	137.4	242.7	388.3	579.9	18	158.6
10	85.1	175.3	309.1	494.0	737.0		
15	131.0	269.8	475.2	758.2	1129.5		
20	177.0	364.2	641.2	1022.2	1521.9		

[a]Source: Sidney Siegel, Nonparametric Statistics, McGraw-Hill, 1956, p. 286 (Reference 40).

SECTION III

OBJECTIVES, CRITERIA, AND ATTRIBUTES

A. INTRODUCTION

In this section, the hierarchy of objectives, criteria, and attributes for evaluating and ranking alternative advanced vehicles is presented. Desirable properties of attributes are described, followed by a statement of the original objectives to be used in evaluating alternative advanced vehicles. Candidates for the objectives, criteria, and attributes are given. Some comments on steps toward a choice of the final attribute set and toward determination of scales for the selected attribute set conclude this section.

There are several purposes to which this section is directed. The first is to explain the concept of a hierarchy of objectives, criteria, and attributes, and which properties are desired of this hierarchy. A second purpose is to provide background information in the form of the original Advanced Vehicle Development Project statement of objectives for the advanced vehicle alternatives. A final purpose is to detail the necessary steps to select the attribute set and its scales for use in the decision model.

B. HIERARCHY OF OBJECTIVES, CRITERIA, AND ATTRIBUTES

There is a structure that permits the transition from a broad statement of objectives to specific, measurable attributes that meet the needs of the decision model used to rank the alternatives (see Figure 2-3). Included in the hierarchy are an overall objective, subobjectives, criteria, and attributes.

Several properties are desired of this hierarchy. First, and most important, the hierarchy should lead to an appropriate ranking of alternatives, which is one that accurately reflects the preferences of the decision-maker. Second, the hierarchy should be reasonably easy to use. Ease of use is critical in order for the ranking to be achieved within time and cost limitations. Some aspects of ease of use include:

(1) Ease of response for those required to provide preferences for the decision model.

(2) Ease of obtaining performance data for alternatives with regard to the attributes.

(3) Ease of carrying out the sensitivity analysis.

The top level in the hierarchy is an overall statement of the objective for the advanced vehicle alternatives. The overall objective for the Advanced Vehicle Project is "... to assess the potential of nonpetroleum passenger vehicles which fully compete with conventional petroleum-fueled heat-engine vehicles in the 1990s" (Reference 41).

The subobjectives provide distinct categories for the components of the overall objective. These components are chosen to facilitate further refinement of the hierarchy. Suggested categories for the subobjectives include economic, operational, and technical objectives.

The level below subobjectives contains criteria. The criteria must permit the quantification of performance of the alternatives with respect to the subobjectives. In other words, the criteria are the highest level elements in the hierarchy that are designed to be, or intended to be, quantifiable. For example, cost is a logical candidate for the criterion related to the economic subobjective.

At the lowest level in the hierarchy are the attributes, which measure the extent to which each of the criteria is satisfied. To give an example, miles per gallon may be an attribute to measure performance with respect to the cost criterion.

The set of attributes to be used when ranking advanced vehicle alternatives must meet several technical requirements. It must be complete enough to include all of the factors that could significantly influence the decision, yet not so large as to overburden those who must provide preferences. Attributes should be carefully selected to avoid redundancy or double counting of the system characteristics. The attributes selected should differentiate between systems by measuring only important advantages and disadvantages inherent in the different types of technologies being considered. For instance, many of the cost factors may be represented by initial cost and life-cycle cost. Other attributes should measure major indicators such as technical, operational, and organizational factors that impinge on the choice of advanced vehicle alternatives.

C. OBJECTIVES FOR ASSESSING ADVANCED VEHICLE ALTERNATIVES

Three "specific objectives of the MDA (Multiattribute Decision Analysis)" are given in Reference 41. These objectives were presented after the overall objective cited earlier:

(1) Determination of the advanced vehicle attribute values and relative weightings that reflect the preferences of decision-makers in the public and private sectors relative to the automotive industry (e.g., range and fuel economy).

(2) Rank the system alternatives with respect to the overall objectives and attributes, based on the system and subsystem assessments.

(3) Perform a sensitivity analysis on the rankings with regard to AV attribute values and the relative weightings.

As a guideline for developing the attributes for the first objective, a list of AV requirements have been developed. Because many powertrain configurations and subsystem alternatives are being considered to overcome deficiencies of the typical electric vehicle, a comparison of vehicle candidates on any meaningful basis requires equalizing as many of the external variables as possible. Thus the Advanced Vehicle Requirements were developed, which specify the vehicle capabilities in terms of its transportation function, i.e., on the basis of passenger/payload capabilities and several minimum performance standards, including range. The various energy storage and propulsion subsystem interactions with the vehicle specifications are worked out, and the final configuration is a result of the vehicle requirements, subsystem characteristics, and control strategy trade-offs. The assumption of an internal combustion engine (ICE) vehicle equivalence for comparison required the development of projected minimum vehicle requirements for the 1990s, based on evolutionary trends. The original set of requirements was circulated to representatives of the auto industry, subsystem manufacturers, and national laboratories for comment. The resulting AV requirements are shown in Table 3-1.

Perhaps the most critical parameters, in terms of the propulsion system design, are acceleration and range. The acceleration requirement is considered to be "diesel-equivalent," which is obviously acceptable to a large population of drivers, even though the performance level is well below the average vehicle on the road. The decisions to purchase diesel vehicles were the results of giving up performance in the interest of fuel economy and perceived reliability. It is difficult to predict if more compromise may be acceptable within a decade, but with the continued availability of conventional cars, present-day diesel-engine vehicle performance was used as a likely limit.

The range of 400 km was chosen to correspond to the 99th percentile daily trip length of the average general-purpose vehicle, to compete with conventional vehicles. This requirement should ease the perception of limited range; however, it is not clear at this time what range is acceptable to the consumer. For example, current four- to five-passenger compact and mid-size cars that are comparable in passenger/payload requirements to the AVs described (i.e., Chevrolet Citation, Pontiac 6000) exhibit ranges of over 600 km (Reference 42). On the other hand, General Research Corporation concluded that the best over-all combination of range, price, and annual cost for the average motorist results in a range of 200 to 240 km from cars with advanced batteries (Reference 43). "Acceptable Range" was investigated further with the automotive industry and consumer representatives using multiattribute decision analysis (see Reference 1).

Two factors that are not obviously important for conventional vehicles, but that can become critical for some AV candidates, are the times needed for start-up and for refueling or recharging. In deference to the known limitations of most AV systems, the times shown in the requirements above have already been extended well beyond their conventional vehicle values towards the perceived limits of consumer tolerance. The minimum recharge times greatly impact vehicle designs, vehicle support systems, and infrastructure requirements.

The Advanced Vehicle Requirements list was used to begin to define the hierarchy of objectives, criteria, and attributes for ranking alternatives. The first task was to separate the objectives to be used in the ranking methodology for alternatives from those objectives that are fixed requirements or constraints.

Table 3-1. Requirements for an Advanced Vehicle

	Requirements	Value
(1)	Passenger capacity	5
(2)	Cargo capacity, ft^3	14.1 to 17.7 (0.4 to 0.5 m^3)
(3)	Payload capacity incl. pass., lb	705 to 904 (320 to 410 kg)
(4)	Max acceleration time to 55 mph (90 km/h), s[a]	20
(5)	Top speed, mph	68 (110 km/h)
(6)	Gradability 55 mph for 3 mi, % (90 km/h for 5 km)	7
	0 to 1.2 mph for starting, % (0 to 2 km/h)	30
(7)	Non-refueled range, EPA U/H, mi	100 to 250 mi (160 to 400 km)
(8)	Refuel time, min	15
(9)	Max start-up time, s	30
(10)	Safety requirements	FMVSS and NHTSA recommendations
(11)	Additional equipment	Heater std., A/C optional
(12)	Vehicle life, mi	100,000 (160,000 km)

[a]Test Payload of 300 lb (136 km).

Good candidates for constraints included requirements (1) through (6), plus (11) and (12). They could be treated as constraints by requiring any advanced vehicle alternative to meet them before being accepted for ranking with regard to the remaining objectives. Good candidates for attributes included requirements (7) through (9) because they can be used effectively to differentiate between alternative advanced vehicle systems.

The objectives of cost minimization, improved vehicle maintainability, safety, and performance were also candidates to aid in the definition of the hierarchy. Objectives, criteria, and attribute sets are discussed below.

D. OBJECTIVES, CRITERIA, AND ATTRIBUTE SETS

Several sets of candidates for use as objectives, criteria, and attributes were developed. While reviewing these sets, it was noted that there were two possibly conflicting objectives for the set chosen for use with the decision model. The criteria and attribute set had to be complete enough to capture the reality of the problem, yet not so large that it overburdened those persons who had to provide their preferences nor those who exercised the decision model and carried out the sensitivity analysis.

The candidate sets of objectives, criteria, and attributes were reviewed by the Advanced Vehicle Development Project staff at JPL. After several iterations, a set for use in the ranking was chosen.

The hierarchy chosen is shown in Figure 3-1. This set includes a single overall objective, four subobjectives (economic, operational, technical, and safety) seven criteria, and eight attributes. With eight attributes, the ranking and sensitivity analysis proved manageable. Also, after the interviews, no significant attribute was found to be missing from the set chosen.

E. DISCUSSION OF ATTRIBUTES

Two cost measures, initial cost and life-cycle cost per mile, were selected. Both costs were measured in 1982 dollars because most of the interviews were conducted in 1982. These two costs were considered most directly related to the choice of an advanced vehicle system. Initial costs are of specific importance to the buyer (consumer or fleet) at the time of sale, while life-cycle cost is important for evaluating the implied operations and maintenance costs over the lifetime of the vehicle.

Four performance measures were selected: relative fuel economy (miles per gallon on an equivalent source-energy basis), refuel time, start-up time, and unrefueled range. The fuel economy ratings were calculated using the energy equivalent units for nonpetroleum fuels. The general response time of the vehicle is characterized by the refuel time and start-up time. The refuel time measure is the time required to refuel the vehicle and the maximum start-up time is the time from vehicle entry until the vehicle can be driven. These measures constitute the most frequent source of operational delays during the lifetime of the vehicle and are of interest to the potential user. The unrefueled ranges were based on trade-offs between the size and type of fuel system and feasible capacity for a given range. The unrefueled range represents the average range of the vehicle between refueling. These four measures of performance were considered most directly related to the choice of advanced vehicle system. Miles-per-gallon equivalent was chosen over other measures of performance, such as efficiency, because of its general familiarity as an index of overall efficiency.

The technical aspects of vehicle availability are summarized with a measure of the intermittent non-availability of the vehicle due to scheduled and unscheduled maintenance problems (maintainability). The maintainability measure encompasses four subdimensions: frequency of service, availability of service facilities, difficulty of repair, and parts availability. The maintainability measure was included to account for the non-economic aspects of maintenance covered by the life-cycle cost attribute. While some of the subdimensions are implicit in the life-cycle cost calculation, the aim here was to address the convenience/inconvenience aspect of maintenance.

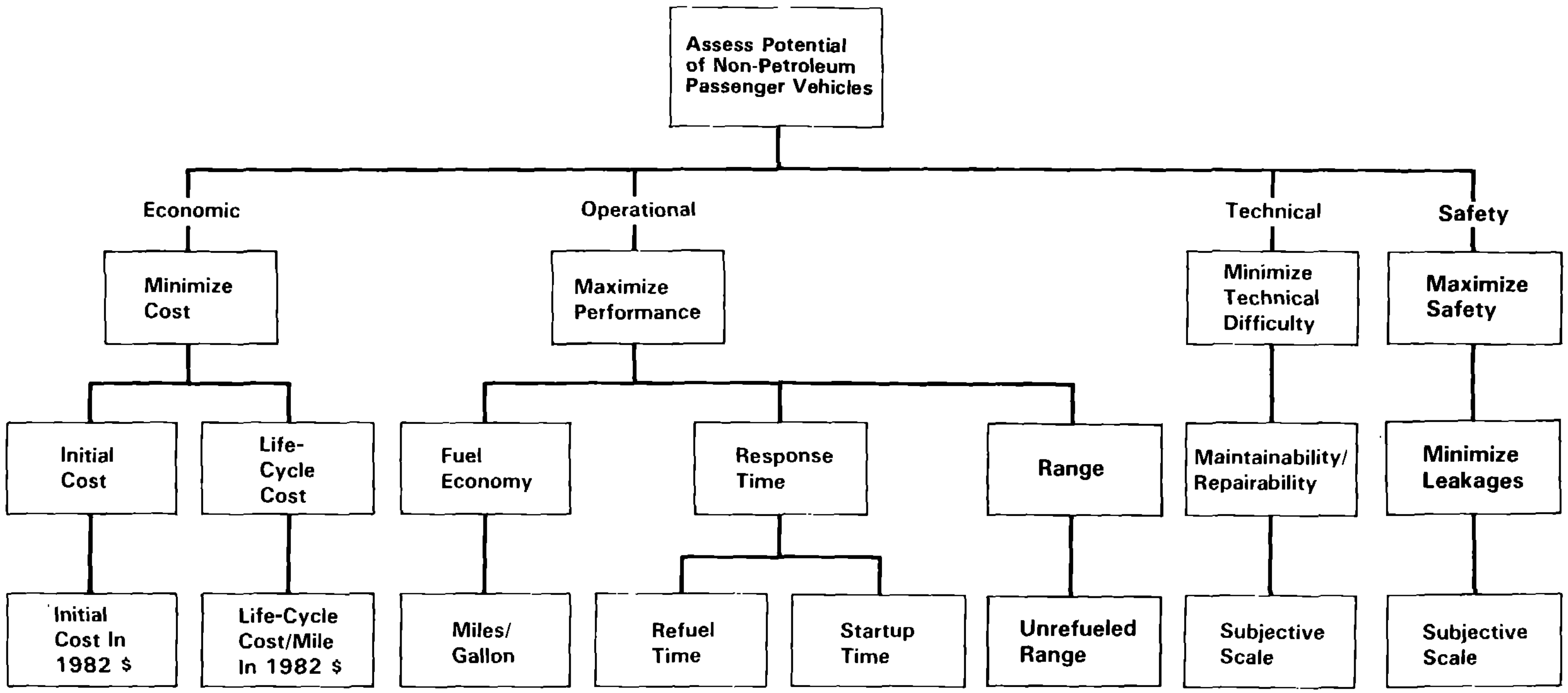


Figure 3-1. Hierarchy of Objectives, Subobjectives, Criteria, and Attributes for Advanced Vehicle Systems

Safety was measured on a scenario scale composed of two subdimensions, low- and high-level risk. The low-level risks refer to the risks of injury from general operation of the vehicle such as low-level exposure to poisonous residual compounds from the recharging process. There could also be minor leakages of fumes or liquids from the fuel system area. The perceived high-level risks are associated with the possible occurrence of a collision in which toxic fumes and/or liquids could enter the vehicle or surrounding area with a possibility of fire and explosion. The two types of risk are synthesized into a scenario measure of safety.

F. DETERMINATION OF ATTRIBUTE SCALES

In order for the decision model to be applied in the ranking effort, a scale for each attribute used had to be developed. Each scale required a unit measure and upper and lower bounds. For example, for the attribute life-cycle cost per mile, 1982 dollars was the unit of measure, and \$0.20/mile and \$1.00/mile were the lower and upper bounds. The list of attributes chosen with the ranges for cost and performance is given in Table 3-2.

The upper and lower bounds for each attribute had to be determined so that all alternatives had performance levels that fit within these bounds. If a performance level had fallen outside one of these bounds, the utility of that performance level could not have been calculated.

Table 3-2. Attributes with Ranges for Cost and Performance

Attribute	Range
(1) Relative fuel economy	20 to 80 mpg equivalent
(2) Initial cost	\$5,000 to \$25,000 (1982\$)
(3) Life-cycle cost/mile	\$0.20 to 1.00 (1982\$)
(4) Maintainability[a]	0 to 10
(5) Safety[b]	0 to 10
(6) Refuel time	0.17 h (10 min) to 8.0 h
(7) Unrefueled range	50 to 250 mi
(8) Maximum start-up time	5 to 600 s (10 min)

[a]See Exhibit 3-1 for maintainability-scale definition.

[b]See Exhibit 3-2 for safety-scale definition.

Exhibit 3-1. Maintainability Scenario Scale

Scenario		Frequency	Availability	Repair difficulty	Parts
Best case	10	Maintenance free	Comparable to ICE	Easily performed	Widely available
	8	Periodic (similar to ICE[a])	Dealerships + many facilities	Comparable to ICE	Most parts stocked
	6	Periodic	Dealerships + some facilities	Moderately difficult	Some parts stocked
	4	Periodic	Dealerships + some facilities	Moderately difficult	Hard to obtain
	2	Regular	Dealerships	Moderately difficult	Not generally available
Worst case	0	Regular	Dealerships	Difficult	Back-ordered

[a]Internal Combustion Engine.

Exhibit 3-2. Safety Scenario Scale

Scenario		Scale
Best case	10	Mitigated risk of leakage, risk of accident leakage lower than for ICE vehicle
	8	Mitigated risk of leakage, risk of accident leakage comparable to ICE
	6	Mitigated risk of operating leakage, moderate risk of accident leakage
	4	Mitigated risk of operating leakage, high risk of accident leakage
	2	Moderate risk of operating leakage, high risk of accident leakage
Worst case	0	High risk of operating leakage, high risk of accident leakage

SECTION IV

ALTERNATIVES AND ATTRIBUTE-STATE DATA

A. INTRODUCTION

This section briefly lists the alternative vehicles ranked by this study and gives the state data for each vehicle. The attributes are described in Section III.

B. ALTERNATIVE VEHICLES

Ten alternative battery technologies were considered: lead-acid, bipolar, nickel-iron, nickel-zinc, zinc-bromine, zinc-chlorine, iron-air, lithium-iron sulfide, sodium-sulfur, and aluminum-air. Also, a baseline internal combustion engine vehicle fueled by methanol and a fuel-cell-powered vehicle were included. Each technology was embodied in a five-passenger vehicle that met the requirements expressed in Table 3-1.

The battery technologies were considered in vehicles configured for 100-, 150-, and 250-mile range without refueling. Not every battery technology was configured for each range. All except aluminum-air were configured for 100- and 150-mile unrefueled range as all-electric vehicles and for 250-mile unrefueled range as hybrid vehicles. The aluminum-air battery technology was considered only as a 250-mile unrefueled range all-electric vehicle. Four other battery technologies were considered as all-electric, 250-mile range vehicles: zine-chlorine, iron-air, lithium-iron sulfide, and sodium-sulfur.

The fuel-cell-powered vehicle was configured for 250-mile unrefueled range. The baseline ICE vehicle was configured for a 250-mile range but was considered over driving cycles for 100- and 150-mile range vehicles as well as a 250-mile-range vehicle.

These alternative vehicle technology/range combinations or advanced vehicle candidates are summarized in Table 4-1. Altogether 23 electric vehicle candidates, 9 hybrid vehicle candidates, and the baseline and fuel-cell vehicles were considered.

C. PROCESS FOR PREPARING ATTRIBUTE-STATE DATA

The Subsystem Technology Assessment included the characterization of advanced versions of passenger vehicles and vans as well as subsystems in terms of performance (power and energy) and those parameters that affect life-cycle cost (production cost, life, efficiency, and maintenance). In the critical area of battery performance and cost projections, several developers were used to define the characteristics of their technologies, and an independent review board was used to assess battery potential in the next decade.

Table 4-1. Five-Passenger Advanced Vehicle Candidates

Technology	EV 100	EV 150	EV 250	HV 250	Baseline	Fuel-Cell
Baseline-ICE					X	
Lead-acid	X	X		X		
Bipolar	X	X		X		
Nickel-iron	X	X		X		
Nickel-zinc	X	X		X		
Zinc-bromine	X	X		X		
Zinc-chlorine	X	X	X	X		
Iron-air	X	X	X	X		
Lithium-iron sulfide	X	X	X	X		
Sodium-sulfur	X	X	X	X		
Aluminum-air			X			
Fuel-cell						X

Vehicle systems analyses began with mission definition, which resulted in performance requirements and annual travel patterns based on a distribution of 24-hour driving schedules. Vehicles with equivalent performance were then conceived from the baseline vehicles and the characteristics of the various subsystems. The vehicles were analyzed, using the JPL/GRC simulation program, ELVEC, which has been updated with advanced vehicle and subsystem characteristics. The vehicle description and energy-use characteristics were used to predict initial and life-cycle costs. Fuel availability and price projections were the subject of the aftermarket analyses.

D. MAINTAINABILITY AND SAFETY ATTRIBUTE-STATE DATA

The maintainability and safety attribute-state data were prepared by the Advanced Vehicle Battery Review Board. These values were based on the technologies used in the vehicles independent of the vehicles' unrefueled range.

Maintainability-state data for the advanced vehicles are shown in Table 4-2. Maintainability for HVs was judged to be 1.0 less than for EVs

Table 4-2. Advanced Vehicle Maintainability Values

Technology	Maintainability (0 to 10 scale, 10 best) for EVs only	Maintainability[a] (0 to 10 scale, 10 best) for HVs only	Maintainability (0 to 10 scale, 10 best) for Baseline-ICE and Fuel-Cell
Baseline-ICE			6
Lead-acid	8	7	
Bipolar	9	8	
Nickel-iron	7.5	6.5	
Nickel-zinc	8.5	7.5	
Zinc-bromine	6	5	
Zinc-chlorine	6	5	
Iron-air	6	5	
Lithium-iron sulfide	7.5	6.5	
Sodium-sulfur	6.5	5.5	
Aluminum-air	5.5	4.5	
Fuel-cell			6

[a]Maintainability for HVs is 1.0 less than for EVs with same battery technology.

with the same battery technology because of the need to maintain a methanol-fueled ICE in the HVs in addition to the battery EV technology. These data conform to the maintainability scenarios of Exhibit 3-1. The advanced vehicle safety-state values are given in Table 4-3. These data conform to the scenarios given in Exhibit 3-2.

Attribute-state data for the eight attributes used to rank the alternative advanced vehicles are given in Tables 4-4, 4-5, and 4-6 for 100-, 150-, and 250-mile-unrefueled range five-passenger vehicles, respectively. Initial costs were rounded to the nearest $100. The attribute-state data were then combined with the preference data obtained from the interviews within the framework described in Section II. The resultant rankings are presented and analyzed in Section VI.

Table 4-3. Advanced Vehicle Safety Values

Technology	Safety (0 to 10, 10 Most Preferred)
Baseline-ICE	6
Lead-acid	10
Bipolar	10
Nickel-iron	7
Nickel-zinc	9
Zinc-bromine	4
Zinc-chlorine	4
Iron-air	6
Lithium-iron sulfide	9
Sodium-sulfur	5
Aluminum-air	6
Fuel-cell	6

Table 4-4. Attribute-State Data for Five-Passenger Advanced Vehicle with 100-Mile Unrefueled Range

Vehicle	Relative fuel economy, mpg	Initial cost, 1982$	Life-cycle cost 1982$ per mi	Maintainability	Safety	Maximum refuel time, h	Unrefueled range, mi	Maximum start time, s
Baseline	48	7,200	0.26	6	6	0.17	100	30
Lead-acid EV	52	13,800	0.28	8	10	8.0		
Bipolar EV	68	12,100	0.25	9	10			
Nickel-iron EV	42	14,800	0.24	7.5	7			
Nickel-zinc EV	57	13,400	0.29	8.5	9			
Zinc-bromine EV	30	13,300	0.31	6	4			
Zinc-chlorine EV	37	15,000	0.31	6	4			
Iron-air EV	33	12,600	0.33	6	6			
Lithium-iron sulfide EV	48	13,300	0.28	7.5	9			
Sodium-sulfur EV	57	14,300	0.31	6.5	5			

Table 4-5. Attribute-State Data for Advanced Vehicle with 150-Mile Unrefueled Range

Vehicle	Relative fuel economy, mpg	Initial cost, 1982$	Life-cycle cost 1982$ per mi	Main-tain-ability	Safety	Maxi-mum refuel time, h	Unre-fueled range, mi	Maxi-mum start time, s
Baseline ICE	47	7,200	0.25	6	6	0.17	150	30
Lead-acid EV	43	17,500	0.29	8	10	8.0	↓	↓
Bipolar EV	56	15,800	0.26	9	10	↓	↓	↓
Nickel-iron EV	36	17,800	0.30	7.5	7.0	↓	↓	↓
Nickel-zinc EV	51	15,500	0.27	8.5	9.0	↓	↓	↓
Zinc-bromine EV	22	17,100	0.34	6	4	↓	↓	↓
Zinc-chlorine EV	30	19,600	0.35	6	4	↓	↓	↓
Iron-air EV	25	16,700	0.35	6	6	↓	↓	↓
Lithium-iron sulfide EV	45	15,200	0.27	7.5	9.0	↓	↓	↓
Sodium-sulfur EV	52	16,500	0.29	6.5	5.0	↓	↓	↓

Table 4-6. Attribute-State Data for Advanced Vehicle with 250-Mile Unrefueled Range

Vehicle	Relative fuel economy, mpg	Initial cost, 1982$	Life-cycle cost 1982$ per mi	Main-tain-ability	Safety	Maxi-mum refuel time, h	Unre-fueled range, mi	Maxi-mum start time, s
Baseline ICE	49	7,200	0.23	6	6	0.17	250	30
Zinc-chlorine EV	28	19,700	0.32	6	4	8.0	↓	↓
Iron-air EV	25	16,100	0.29	6	6	8.0		
Lithium-iron sulfide EV	41	19,300	0.29	7.5	9	8.0		
Aluminum-air EV	20	18,400	0.45	5.5	6	0.5		
Sodium-sulfur EV	50	18,300	0.29	6.5	5	8.0		
Fuel-cell	58	17,600	0.31	6	6	0.17		
Lead-acid HV	48	14,900	0.29	7	10	↓		
Bipolar HV	61	12,700	0.25	8	10			
Nickel-iron HV	39	16,300	0.29	6.5	7			
Nickel-zinc HV	51	13,700	0.28	7.5	9			
Zinc-bromine HV	31	15,200	0.32	5	4			
Zinc-chlorine HV	35	17,200	0.31	5	4			
Iron-air HV	33	14,600	0.35	5	6			
Lithium-iron sulfide HV	43	15,500	0.30	6.5	9			
Sodium-sulfur HV	52	15,000	0.32	5.5	5			

SECTION V

INTERVIEWS

A. INTRODUCTION

The methodology described in Section II requires preference information from individuals as well as attribute-state data to produce a ranking of alternative vehicle systems. The preference information required for each individual interviewed includes a scaling constant and a utility function for each attribute. Interviewees were sought who had significant knowledge of, and interest in, advanced vehicle systems and who were regarded as decision-makers within their organizations.

This section lists the organizations interviewed to obtain preference data and gives examples of the questions posed to them. The full set of questions is contained in Reference 1. A summary of the interview results is also given in this section.

B. INTERVIEWEES

The desired interviewees were persons who would either have a direct role in the ultimate development of advanced vehicle systems or who act as advisors in the decision-making process. Representatives were sought from a variety of organizations, including:

(1) Advanced vehicle fleet involvement either in fleet purchasing or management.

(2) Automobile manufacturing advanced vehicle research within a major automobile manufacturing company.

(3) Automobile manufacturing corporate decision-makers with interests in advanced vehicles.

(4) Consumer, professional, and market-analysis organizations with an interest in advanced vehicles.

(5) Fuel suppliers to advanced vehicle markets.

(6) Research organizations conducting research in the advanced vehicle area for utility companies.

(7) Utility companies with an interest in advanced vehicles.

Altogether, a total of 40 persons were interviewed between October 15, 1982, and January 17, 1983. They included four individuals from the advanced vehicle fleet category, eleven from the automobile manufacturing research and corporate level, one from the consulting/professional category, four from the consumer category, five from the fuel suppliers, three from the research area, and six from the utility industry. Interviews were also conducted with the U.S. Department of Energy and Jet Propulsion Laboratory personnel as an internal exercise. The results of one interview were incomplete and were not included in the analysis. Accordingly, 39 complete interviews form the corpus of the analysis.

The 39 individuals came from 24 organizations. A list of those organizations not requesting anonymity is shown in Table 5-1. They consist of one corporate president, one chairman, three vice presidents, four directors, one general manager, four program/project managers, two division/department heads, ten managers, two supervisors, one senior research scientist, one senior commercial representative, and nine engineers, specialists, and technical staff members. This group comprises a significant cross-section of interested parties concerned with advanced vehicle systems.

The representation of members in the sample was constituted from an initial survey of representatives derived from conference agendas, personal contacts, and referrals. This "snowball" sampling approach was further refined during the interviews as additional recommendations were made. These recommendations were then reviewed for inclusion in the study. While this sample is not a random one, there were numerous individuals who simply had to be included because they had played a key role in some aspect of advanced vehicle research or use. Using a random sampling design and possibly omitting them from the survey would have left serious gaps in the results of the study. Furthermore, a larger, random sample would tend to move the results toward some "average" set of responses. The aim of this study was to survey those at the leading edge of advanced vehicle research and use to obtain an informed, critical response as opposed to an average or typical response. Although more interviews might have been desirable, the time and resources to accomplish them was not available.

C. INTERVIEW PROCESS

The selected personnel were asked to provide their inputs to the rankings during one-hour interviews although, in fact, the interviews ranged from 20 to 100 minutes. These sessions were structured to acquire the interviewee's utility functions and scaling constants with regard to the attributes chosen for the purpose of ranking alternative advanced vehicle systems.

There were five steps in the decision-analysis interview, as shown in Figure 5-1. The first step provided an introduction to the interview and afforded the opportunity to have the interviewee's questions about the process answered. Next, the interviewee's utility function for each attribute was obtained by asking a series of preference questions. Following that, independence was checked by asking if the responses to those questions would vary with changes in the levels of the other attributes (i.e., attributes other than the one whose utility function was being assessed). The fourth step in the interview involved having the interviewee rank the attributes in order of importance. This provided a consistency check to aid with the final step, the acquisition of the interviewee's scaling constant for each attribute. The ranking of attributes helped guide the responses to the questions on scaling constants.

Table 5-1. Categorical Summary of Organizations not Requesting Anonymity Whose Representatives Were Interviewed

Organization	Type	Location
American Automobile Association	Consumer	Falls Church, VA
BKM	Consultants	San Diego, CA
Bank of America	AV fleet involvement	San Francisco, CA
California Energy Commission	AV fleet involvement	Sacramento, CA
Conoco Coal Development Co.	Fuel supplier	Stamford, CT
Consumer Reports	Consumer	Orange, CT
Detroit Edison	Utility	Detroit, MI
Electric Power Research Institute	Research/utility	Palo Alto, CA
Energy Transition Corporation	Fuel supplier	Santa Fe, NM
Future Fuels of America	Fuel supplier	Sepulveda, CA
GMC Truck and Coach Div. of General Motors	Automobile mfg research	Pontiac, MI
GTE Service Corporation	AV fleet involvement	Stamford, CT
General Motors Research Laboratories	Automobile mfg research	Warren, MI
Long Island Lighting Co.	Utility	Minneola, NY
Philadelphia Electric Co.	Utility	Philadelphia, PA
J. D. Power and Associates	Market analysis	Westlake Village, CA
Southern California Edison Co.	Utility	Rosemead, CA

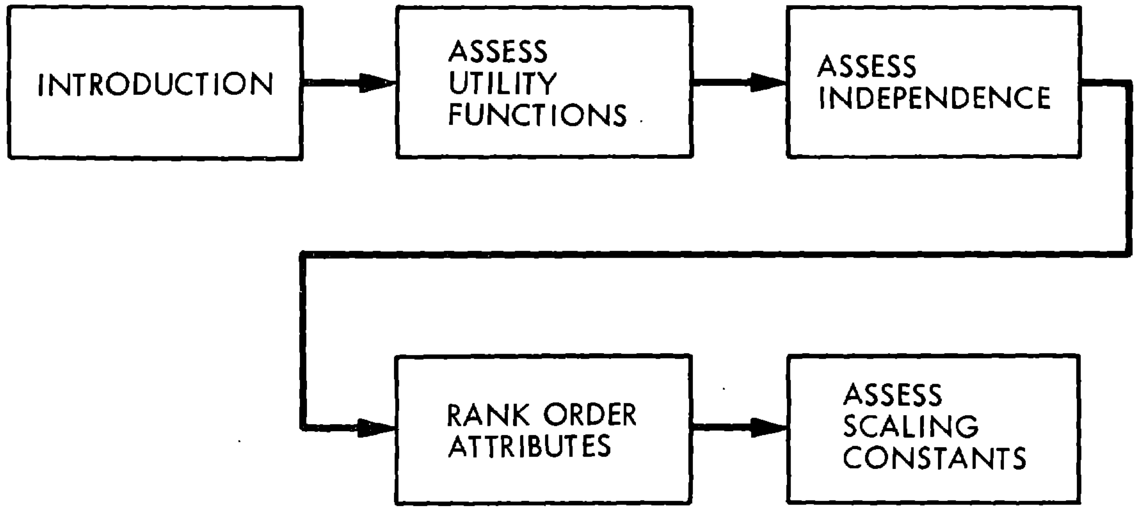


Figure 5-1. Decision-Analysis Interview Flow Chart

D. SAMPLE QUESTIONS

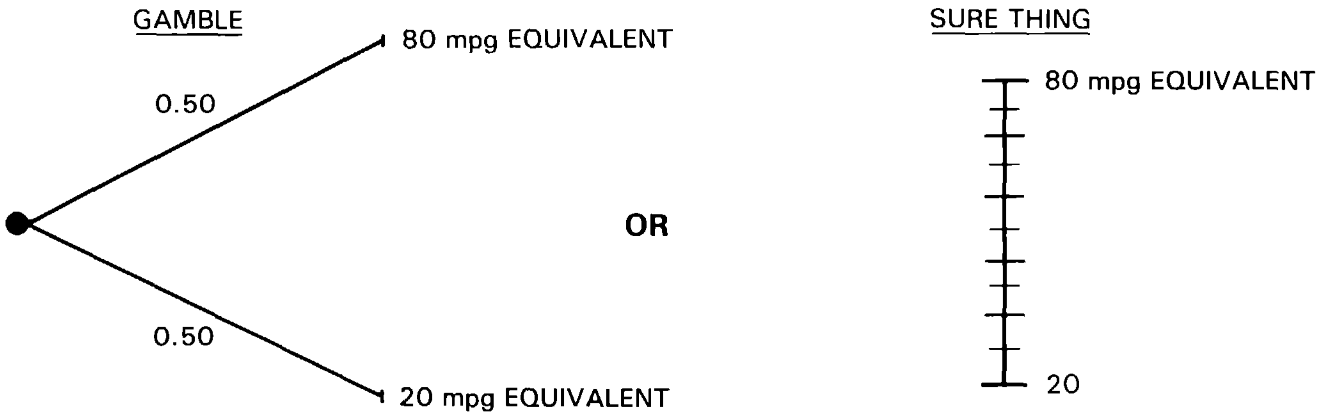
Sample questions for the interviews are shown in Figures 5-2, 5-3, and 5-4. Figure 5-2 contains a sample question used to obtain information that enabled the construction of the individual's utility function for the attribute "miles per gallon equivalent." Figure 5-3 contains a sample question for the ranking of attributes in order of importance, while Figure 5-4 shows a sample question for obtaining the scaling constant for an attribute. The full questionnaire used is contained in Reference 1.

E. INTERVIEW PROCESS REFERENCES

The use of interviews in the decision-analysis process is well established and documented. Excellent descriptions of decision analysis with interviews are provided by Raiffa, Schlaifer, and Winkler (see References 4, 6, and 24). References on decision-analysis interviews especially well-suited to the manager include Brown, Kahr, and Peterson (see Reference 21) and Huber (Reference 44). Chapter 4 of Huber's book contains two case studies involving multiattribute decision-making. The authoritative book by Keeney and Raiffa (see Reference 2) contains a variety of case studies in multiattribute decision-making. Most of these cases are in Chapter 7, but one, involving airport development, described in detail in Chapter 8, includes responses to interview questions on utilities, independence, and scaling constants. References covering interviews to obtain probability estimates are Hogarth (see Reference 22) and Spetzler and Stael von Holstein (see Reference 23). The latter describes the SRI approach to probability encoding.

F. INTERVIEW RESULTS

On the whole, the interviews went rather smoothly. All interviewees were able to provide the information needed to form their attribute utility functions and scaling constants. The average length of the interview was



- **FOR WHICH VALUE OF THE "SURE THING" ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?**

  INDIFFERENCE POINT ______

- **IF YOU KNEW THAT ALL OTHER ATTRIBUTES WERE AT THEIR WORST STATES?**

  INDIFFERENCE POINT ______

- **IF YOU KNEW THAT ALL OTHER ATTRIBUTES WERE AT THEIR BEST STATES?**

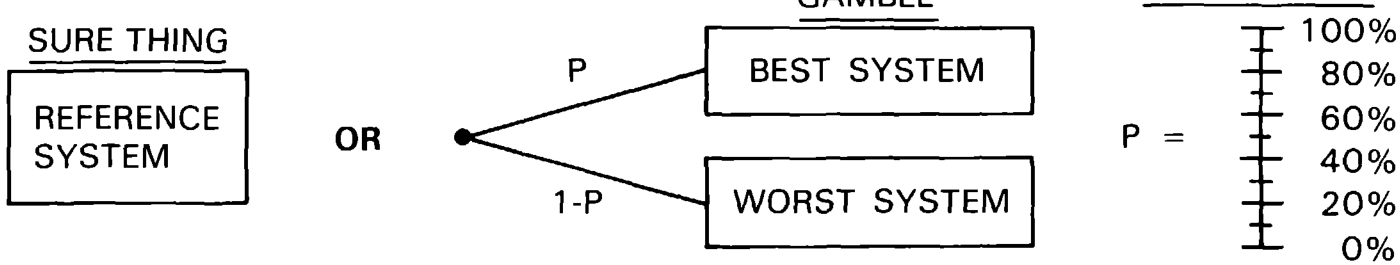
  INDIFFERENCE POINT ______

Figure 5-2. Sample Interview Question: Relative Fuel Economy

ATTRIBUTE	RELATIVE FUEL ECONOMY	INITIAL COST IN 1982$	LIFE-CYCLE COST/MILE IN 1982$	MAINTAIN-ABILITY	SAFETY	REFUEL TIME	UNRE-FUELED RANGE	MAXIMUM STARTUP TIME
Best State	80 miles per gallon equivalent	$5,000	$0.20/mile	10	10	0.17 hours (10 minutes)	250 miles	5 seconds
Worst State	20 miles per gallon equivalent	$25,000	$1.00/mile	0	0	8.0 hours	50 miles	600 seconds (10 minutes)
Order of Importance								

Figure 5-3. Sample of Interview Question: Order of Attribute Importance

FOR WHAT VALUE OF P ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE"?



	RELATIVE FUEL ECONOMY	INITIAL COST IN 1982$	LIFE-CYCLE COST/MILE	MAINTAIN-ABILITY	SAFETY	REFUEL TIME	UNREFUELED RANGE	MAXIMUM STARTUP TIME
REFERENCE:	80 mpg eq.							
		$25,000	$1.00/mile	0	0	8 hours	50 miles	600 seconds
BEST:	80 mpg eq.	$5,000	$0.20/mile	10	10	.17 hours	250 miles	5 seconds
WORST:								
	20 mpg eq.	$25,000	$1.00/mile	0	0	8 hours	50 miles	600 seconds

WHAT DO YOU WIN, IF YOU WIN THE GAMBLE?
WHAT DO YOU LOSE, IF YOU LOSE THE GAMBLE?

Figure 5-4. Sample Interview Question: Importance of Relative Fuel Economy

69 minutes with the longest session completed in 100 minutes and the shortest in 20 minutes. There was one interview (3%) under 40 minutes; six interviews (15%) between 40 and 50 minutes; thirteen interviews (33%) taking 60 minutes; nine interviews (23%) between 70 and 90 minutes; four interviews (10%) taking 90 minutes; and six interviews (15%) taking 100 minutes. All 39 interviews were completed within 100 minutes, with thirty-three (85%) at or less than 90 minutes.

The responses for the interviewees to the questions designed to elicit information needed to determine their attribute utility functions are summarized in Table 5-2 for the entire sample. Table 5-3, (a) through (g), shows the results by group. As shown, there was a willingness in many cases to take a risk to obtain good (rather than average) maintainability and safety.

Responses to the questions asking interviewees to rank the importance of each of the attributes are summarized for each group and the entire sample in Table 5-4. The ranking for each group was determined by taking the sum of the individual rankings within that group and placing the lowest sum as first in rank, the next lowest sum second, and so on.

Overall, initial cost and safety were most important, and refuel time and maximum start-up time least important (see also Table 5-5). It is interesting to note that the consumer/market, analysis/professional group ranked safety last. This may be due (based on comments made during the interviews) to survey data (cited during interviews) indicating that consumers tend to disregard safety at the point-of-sale. The unrefueled range was not as important to the AV fleet and auto manufacturer groups as it was to the utilities (presumably due to capacity expansion concerns).

Table 5-2. Preference Data for all Interviews

Attribute	Attribute question range	Response range	Median certainty equivalent	Number of interviewees who are: Risk averse	Risk neutral	Risk prone
Relative fuel economy	20 to 80 mpg	23 to 73 mpg	47.5 mpg	22	8	9
Initial cost	$5000 to 25,000	$5500 to 22,500	$12,500	26	7	6
Life-cycle cost	$0.20 to 1.00/mi	$0.22 to 0.90/mi	$0.40/mi	27	9	3
Maintainability	0 to 10	1.5 to 9.5	6	4	9	26
Safety	0 to 10	1 to 10	7	4	4	31
Max refuel time	0.17 to 8.0 h	0.20 to 8.0 h	2 h	28	6	5
Unrefueled range	50 to 250 mi	60 to 230 mi	125 mi	22	9	8
Max start-up time	5 to 600 s	7 to 510 s	120 s	30	5	4

Table 5-3. Preference Data for Interviews by Group

(a) AV Fleet Involvement

Attribute	Attribute question range	Response range	Median certainty equivalent	Number of interviewees who are		
				Risk averse	Risk neutral	Risk prone
Relative fuel economy	20 to 80 mpg	24 to 60 mpg	38 mpg	4		
Initial cost	$5000 to 25,000	$7000 to 18,000	$13,000	3		1
Life-cycle cost	$0.20 to 1.00/mi	$0.23 to 0.65/mi	$0.35/mi	3	1	
Maintainability	0 to 10	4 to 8.5	7			4
Safety	0 to 10	4 to 9	7			4
Max refuel time	0.17 to 8.0 h	0.25 to 4.5 h	3 h	3		1
Unrefueled range	50 to 250 mi	60 to 212 mi	150 mi	2	1	1
Max start-up time	5 to 600 s	7 to 420 s	270 s	3		1

Table 5-3. (Cont'd)

(b) Automobile Manufacturer Research

Attribute	Attribute question range	Response range	Median certainty equivalent	Number of interviewees who are		
				Risk averse	Risk neutral	Risk prone
Relative fuel economy	20 to 80 mpg	30 to 70 mpg	51 mpg	2	2	4
Initial cost	\$5000 to 25,000	\$5500 to 20,000	\$11,000	5	3	
Life-cycle cost	\$0.20 to 1.00/mi	\$0.22 to 0.80/mi	\$0.38/mi	6	2	
Maintainability	0 to 10	2.5 to 9.1	6	1	3	4
Safety	0 to 10	1 to 9.9	6	2		6
Max refuel time	0.17 to 8.0 h	0.50 to 6.0 h	2 h	6	2	
Unrefueled range	50 to 250 mi	60 to 200 mi	113 mi	6	1	1
Max start-up time	5 to 600 s	15 to 450 s	45 s	7	1	

Table 5-3. (Cont'd)

(c) Automobile Manufacturer/Corporate

Attribute	Attribute question range	Response range	Median certainty equivalent	Number of interviewees who are: Risk averse	Risk neutral	Risk prone
Relative fuel economy	20 to 80 mpg	60 to 72.5 mpg	65 mpg			3
Initial cost	$5000 to 25,000	$5500 to 22,500	$10,000	2		1
Life-cycle cost	$0.20 to 1.00/mi	$0.25 to 0.35/mi	$0.30/mi	3		
Maintainability	0 to 10	6 to 9	8			3
Safety	0 to 10	7.5 to 9	8			3
Max refuel time	0.17 to 8.0 h	0.25 to 4.0 h	0.50 h	3		
Unrefueled range	50 to 250 mi	75 to 100 mi	100 mi	3		
Max start-up time	5 to 600 s	20 to 500 s	60 s	2	1	

Table 5-3. (Cont'd)

(d) Consumer/Market Research/Professional

Attribute	Attribute question range	Response range	Median certainty equivalent	Number of interviewees who are		
				Risk averse	Risk neutral	Risk prone
Relative fuel economy	20 to 80 mpg	25 to 67.5 mpg	50 mpg	2	2	1
Initial cost	$5000 to 25,000	$7000 to 20,000	$12,500	3	1	1
Life-cycle cost	$0.20 to 1.00/mi	$0.25 to 0.80/mi	$0.50/mi	3	2	
Maintainability	0 to 10	4 to 9.5	7		1	4
Safety	0 to 10	6 to 9	7	1		4
Max refuel time	0.17 to 8.0 h	0.20 to 3.5 h	0.50 h	5		
Unrefueled range	50 to 250 mi	60 to 230 mi	150 mi	2	1	2
Max start-up time	5 to 600 s	10 to 240 s	30 s	4	1	

Table 5-3. (Cont'd)

(e) Fuel Suppliers

Attribute	Attribute question range	Response range	Median certainty equivalent	Number of interviewees who are: Risk averse	Risk neutral	Risk prone
Relative fuel economy	20 to 80 mpg	23 to 65 mpg	40 mpg	5		
Initial cost	$5000 to 25,000	$7000 to 20,000	$10,000	5		
Life-cycle cost	$0.20 to 1.00/mi	$0.23 to 0.80/mi	$0.45/mi	4	1	
Maintainability	0 to 10	2 to 8.5	7	1	1	3
Safety	0 to 10	3 to 10	5.5		1	4
Max refuel time	0.17 to 8.0 h	0.33 to 6.0 h	3.5 h	3	1	1
Unrefueled range	50 to 250 mi	80 to 240 mi	125 mi	3		2
Max start-up time	5 to 600 s	40 to 510 s	270 s	3	1	1

Table 5-3. (Cont'd)

(f) Research/Utility

Attribute	Attribute question range	Response range	Median certainty equivalent	Number of interviewees who are: Risk averse	Risk neutral	Risk prone
Relative fuel economy	20 to 80 mpg	28 to 65 mpg	45 mpg	2	1	
Initial cost	\$5000 to 25,000	\$7500 to 20,000	\$15,000	1	1	1
Life-cycle cost	\$0.20 to 1.00/mi	\$0.40 to 0.90/mi	\$0.60/mi		2	1
Maintainability	0 to 10	1 to 8	5	1	1	1
Safety	0 to 10	1 to 9.5	9	1		2
Max refuel time	0.17 to 8.0 h	0.75 to 8.0 h	6.0 h		1	2
Unrefueled range	50 to 250 mi	100 to 200 mi	150 mi		3	
Max start-up time	5 to 600 s	45 to 510 s	360 s	2		1

Table 5-3. (Cont'd)

(g) Utility

Attribute	Attribute question range	Response range	Median certainty equivalent	Number of interviewees who are Risk averse	Risk neutral	Risk prone
Relative fuel economy	20 to 80 mpg	35 to 65 mpg	53 mpg	3	2	1
Initial cost	$5000 to 25,000	$6750 to 20,000	$15,000	3	1	2
Life-cycle cost	$0.20 to 1.00/mi	$0.24 to 0.85/mi	$0.49/mi	4		2
Maintainability	0 to 10	1.5 to 8	5.8	1	2	3
Safety	0 to 10	2.5 to 8	5.5		1	5
Max refuel time	0.17 to 8.0 h	0.67 to 6.0 h	1.5 h	4	2	
Unrefueled range	50 to 250 mi	80 to 195 mi	118 mi	4		2
Max start-up time	5 to 600 s	10 to 420 s	210 s	4	1	1

Table 5-4. Preference Data from Interviews: Importance of Attributes

Attribute	Rank Sum Rule Rankings							
	AV fleet involvement	Auto mfg/ Research	Auto mfg/ Corporate	Consumer/ Market research/ Professional	Fuel suppliers	Research/ Utility	Utility	Overall
Relative fuel economy	7	4-5	2-3	2	2	5	8	5
Initial cost	2	2	4	1	1	3	4	1
Life-cycle cost	1	4-5	5	3	3	4	5	3
Maintainability	5	3	2-3	7	8	2	3	4
Safety	3	1	1	8	5	1	2	2
Refuel time	4	7	8	5	7	8	7	8
Unrefueled range	8	8	7	4	4	6	1	6
Maximum start-up time	6	6	6	6	6	7	6	7

Table 5-5. Ranking of Attribute Importance

Attribute	Number of times rated: Most important	Number of times rated: Least important
Relative fuel economy	5	5
Initial cost	13	6
Life-cycle cost	5	5
Maintainability	0	5
Safety	18	7
Maximum refuel time	2	17
Maximum start-up time	2	15
Range	3	8

SECTION VI

RANKING ANALYSIS AND DISCUSSION

A. INTRODUCTION

The results of 39 successfully conducted interviews were analyzed by several different methods. Preference data were elicited from the interviewees regarding the eight attributes for use within a multiattribute decision-analysis model.

The 39 interviews were classified into eight groups, with three to eight interviews in a group. The eight groups were generically classified as:

Group 1: AV fleet.

Group 2: Automotive research.

Group 3: Automotive corporate.

Group 4: Automotive consumer/Market research/Professional.

Group 5: DOE/JPL.

Group 6: Alternative fuel suppliers.

Group 7: Utility research.

Group 8: Electric utilities.

The rankings were developed by interviewee and by group. Three group-decision rules were used for the groups: (1) The Additive Rule, (2) The Nash Bargaining Rule, and (3) The Rank Sum Rule.

Attribute-state data used in these rankings are given in Tables 4-4, 4-5, and 4-6. Additional insights can be gained by referring to the attribute-state data while studying the rankings presented in this section.

B. RANKING PROCESS

The five-passenger advanced vehicle technologies evaluated and ranked include a baseline methanol-fueled internal combustion engine, a fuel cell, an aluminum-air electric vehicle, and both hybrid and electric vehicles for lead-acid, bipolar, nickel-iron, nickel-zinc, zinc-bromine, zinc-chlorine, iron-air, lithium-iron sulfide, and sodium-sulfur battery systems. Vehicle designs for 100- and 150-mile range were assessed for all EVs except aluminum-air. Electric vehicle designs with 250-mile range were assessed only for zinc-chlorine, iron-air, lithium-iron sulfide, sodium-sulfur, and aluminum-air. The fuel-cell and hybrid vehicles were all designed for a 250-mile range. The baseline methanol ICE vehicle was designed for a 250-mile range but evaluated over 100-, 150-, and 250-mile range driving cycles to compare with vehicles of each range. These 34 vehicle technology/range combinations are displayed in Table 4-1.

Rankings were calculated for individuals and the eight groups for both multiplicative and additive utility models. The multiplicative model was used for its theoretical rigor and the additive model for its ease of understanding.

Rankings were calculated using the MATEUS computer program (described in Reference 1) on an AODC microcomputer. At most, ten vehicles were ranked each time due to a combination of limitations. The ten-vehicle limit led to a series of rankings being conducted.

C. RANKINGS OVERVIEW

The series of rankings was conducted to answer a structured set of questions. First, each battery technology was considered separately. The question to be answered was: What is the most-preferred-range vehicle for the battery technology - 100, 150, or 250 miles? Second, each range was considered separately and the question was: What is the most-preferred battery technology for this range? For the 250-mile range, EVs were initially considered separately from HVs.

The rankings resulting from the first two questions were used to generate candidates for the ranking conducted to answer the third question: What are the most promising technology/range combinations for electric vehicles? The top-ranked electric vehicles were then ranked against the baseline ICE and the most-preferred of the HVs to answer the final question: How do the most-preferred of the EVs compare with those vehicles?

To summarize, the series of rankings was directed to illuminate:

(1) Which vehicle technology/range combinations are most preferred?

(2) Where do the most promising EVs stand with regard to the baseline ICE vehicle and the promising HVs?

(3) What attributes are significantly affecting the rankings of EVs?

D. MOST-PREFERRED RANGE FOR EACH TECHNOLOGY

The first set of rankings involved ten runs, one for each of nine battery technologies and one for a baseline ICE considered for 100-, 150-, and 250-mile-unrefueled-range driving cycles. In each run, rankings were calculated for the eight groups. These runs were directed toward finding the most-preferred range for each technology. The candidate vehicles for each battery technology included a 100-mile EV, 150-mile EV, 250-mile HV, and for the zinc-chlorine, iron-air, lithium-iron sulfide, and sodium-sulfur technologies, a 250-mile EV.

The rankings were fairly consistent across the nine battery technologies. Top-ranked was the 250-mile HV, followed by the 250-mile EV (when available for that technology). Then, for six of the nine battery technologies, the 100-mile vehicle was preferred to the 150-mile vehicle. These six were: lead-acid, bipolar, nickel-iron, iron-air, zinc-chlorine, and zinc-bromine. For the other three battery technologies (nickel-zinc, sodium sulfur and lithium-iron sulfide) the 100-mile and 150-mile EVs were about equally ranked. For the baseline ICE, the 250-mile cycle was top-ranked, followed by the 150-mile, with the 100-mile cycle third. The only group that consistently preferred 150-mile to 100-mile vehicles was electric utilities. These rankings are summarized in Table 6-1.

The key attributes that affected these rankings by range for a technology were initial cost and, of course, range. The preference of 100-mile vehicles over 150-mile vehicles for six of the nine battery technologies reflected the preference that the additional range was not worth the additional initial cost.

E. MOST-PREFERRED ELECTRIC VEHICLE TECHNOLOGY FOR EACH RANGE

The second set of rankings included three runs directed to identify the most-preferred electric vehicle technologies for each range. Thus, nine battery technologies and the baseline ICE were ranked for 100-mile and 150-mile ranges. For the 250-mile range, five battery technologies plus the baseline ICE and a fuel-cell vehicle were ranked. These five technologies were: lithium-iron sulfide, sodium-sulfur, iron-air, aluminum-air, and zinc-chlorine.

The results of these three rankings are summarized in Table 6-2. In the 100- and 150-mile cases, the baseline ICE, bipolar, lead-acid, and nickel-zinc battery technology vehicles top the rankings. Middle-ranked are lithium-iron sulfide, nickel-iron, and sodium sulfur. Lowest-ranked are iron-air, zinc-chlorine, and zinc-bromine battery technology vehicles.

Table 6-1. Ranking by Range for Each Five-Passenger-Vehicle Technology

250-mi HYBRID VEHICLES MOST PREFERRED
↓
250-mi ELECTRIC VEHICLES (WHEN AVAILABLE)
↓
100-mi ELECTRIC VEHICLES
↓
150-mi ELECTRIC VEHICLES LEAST PREFERRED

EXCEPTIONS:
1) NICKEL-ZINC, SODIUM-SULFUR, AND LITHIUM-IRON SULFIDE, 100-mi AND 150-mi VEHICLES ABOUT EVEN IN RANKING
2) ELECTRIC UTILITY REPRESENTATIVES PREFER 150-mi-RANGE VEHICLES TO 100-mi-RANGE VEHICLES

Table 6-2. Ranking by Electric-Vehicle Technology for Each Range

	100-MI 5-PASSENGER		150-MI 5-PASSENGER		250-MI 5-PASSENGER	
MOST PREFERRED	1	BIPOLAR	1-2	BASELINE	1	BASELINE
			1-2	BIPOLAR		
	2-3	BASELINE			2-3	FUEL CELL
	2-3	LEAD-ACID	3-4	LEAD-ACID	2-3	LI/FES
			3-4	NICKEL-ZINC		
	4	NICKEL-ZINC			4	NA/S
			5	LI/FES		
	5	LI/FES			5	IRON-AIR
			6-7	NA/S		
	6	NI/FE	6-7	NI/FE	6	ALUM-AIR
	7	NA/S	8	IRON-AIR	7	ZN/CL_2
	8	IRON-AIR	9-10	ZN/CL_2		
			9-10	ZN/BR_2		
	9-10	ZN/CL_2				
LEAST PREFERRED	9-10	ZN/BR_2				

Most interesting, perhaps, of the 100- and 150-mile rankings is that the bipolar battery technology vehicle tops the baseline ICE at the 100-mile range and is as preferred at the 150-mile range. This is somewhat surprising because the 100-mile bipolar vehicle costs initially $4,900 more than the baseline ICE while the 150-mile bipolar vehicle has an $8,600 cost disadvantage. Another disadvantage of the bipolar vehicle is a maximum refuel time of eight hours as opposed to ten minutes. The bipolar vehicle's advantages lie in better safety and maintainability assessments and slightly better fuel economy.

The key attributes affecting the middle- and lower-ranked vehicles are maintainability and safety. Initial cost and relative fuel economy have a lesser effect on these rankings.

When the 250-mile EVs are ranked with the baseline ICE and the fuel-cell vehicle, the baseline ICE clearly ranks highest with a significant advantage in initial cost ($8,900 or more) and in maximum refuel time. Following the baseline ICE are the fuel-cell vehicle and the lithium-iron sulfide EV. The fuel-cell vehicle's ranking is enhanced by its brief maximum refuel time while the lithium-iron sulfide EV is helped by its relatively better maintainability and safety values. Next in the rankings is sodium-sulfur, followed by iron-air, aluminum-air, and zinc-chlorine. Aluminum-air is marked by low fuel economy and high life-cycle cost, while the zinc-chlorine vehicle is hampered by a relatively low safety rating.

F. MOST PREFERRED OF HYBRID VEHICLES AND BASELINE ICE

The next set of rankings involved nine battery technologies configured with a methanol-fueled ICE to form hybrid vehicles with a 250-mile range. The baseline ICE evaluated for a 250-mile driving cycle was included. The nine battery technologies were those used in the 100- and 150-mile EVs, namely: bipolar, lead-acid, nickel-zinc, lithium-iron sulfide, nickel-iron, sodium-sulfur, iron-air, zinc-chlorine and zinc-bromine.

The results of these rankings are displayed in Table 6-3. Perhaps surprisingly, the bipolar HV ranked first, the lead-acid HV second, and the baseline ICE ranked third with the nickel-zinc HV. Although the baseline ICE had a substantial initial cost advantage over the HVs, the bipolar HV's top ranking was due to its superior maintainability and safety over all other 250-mile vehicles and to its initial cost advantage over the other HVs. The middle-ranked vehicles (lithium-iron sulfide, nickel-iron, and sodium-sulfur) had the middle-valued maintainability and safety values. In the lowest-ranked vehicles, iron-air, zinc-chlorine, and zinc-bromine had among the lowest maintainability, safety, and relative fuel-economy values.

G. MOST PREFERRED OF ELECTRIC VEHICLES

The rankings described in Section VI-D to identify the most-preferred-range vehicle for each battery technology served to provide the vehicles to be ranked in this section. The objective here was to identify the most-preferred electric vehicles in terms of battery technology/range combinations.

Table 6-3. Ranking by Hybrid-Vehicle Technology for 250-mi-Range Vehicle

MOST PREFERRED	1	BIPOLAR
↓	2	LEAD-ACID
	3-4	BASELINE
	3-4	NICKEL-ZINC
	5	LITHIUM-IRON SULFIDE
	6	NICKEL-IRON
	7	SODIUM-SULFUR
	8	IRON-AIR
LEAST PREFERRED	9-10	ZINC-CHLORINE
	9-10	ZINC-BROMINE

Although there were nine battery technologies with alternative ranges considered, one of the technologies, nickel-zinc, had a tie for its 100- and 150-mile vehicles. Therefore, two nickel-zinc EVs were considered along with one each of the eight other technologies. The specific EVs ranked were:

Technology	Range, mi
Lead-acid	100
Bipolar	100
Nickel-iron	100
Zinc-bromine	100
Nickel-zinc	100
Nickel-zinc	150
Zinc-chlorine	250
Iron-air	250
Lithium-iron sulfide	250
Sodium-sulfur	250

The attribute data for these ten electric vehicles are given in Table 6-4. A brief comparison of these data with the attribute state ranges of Table 5-7 reveals that the greatest variation of the attribute data in terms of its range from best state to worst state occurs for unrefueled range, safety, and relative fuel economy. Two attributes, maximum start-up time and maximum refuel time were equal for all ten vehicles. The other three attributes revealed little to moderate variation.

Rankings were calculated, using both the multiplicative and additive utility models described in Section II. The preference data elicited during the interviews summarized in Section V was used for the multiplicative model while normalizing the scaling constants to sum to 1.0 was done to employ the additive model.

Rankings for the multiplicative model are shown in Table 6-5 while rankings for the additive model are shown in Table 6-6. Two general comments are appropriate. First, there is fairly good agreement between the rankings of the multiplicative and additive models for each group. Differences are limited to one or two positions in rank. Second, there is considerable variation among the groups for several of the vehicles, notably the lead-acid, nickel-zinc and lithium-iron sulfide. These differences are due to the different importance of the attributes given by each group as shown in Table 5-4.

Table 6-4. Attribute Data for Rankings Involving Most-Preferred Range for Each Electric Vehicle Technology

VEHICLE	RELATIVE FUEL ECON., mi/gal	INITIAL COST, 1982 $	LCC, $/mi 1982 $	MAINTAIN-ABILITY	SAFETY	MAXIMUM REFUEL TIME, h	RANGE, mi	MAXIMUM START TIME, s
PB/AC EV-100	52	13800	0.28	8	10	8	100	30
BIPOLAR EV 100	68	12100	0.25	9	10	8	100	30
NI/FE EV 100	42	14800	0.24	7.5	7	8	100	30
NI/ZN EV 100	57	13400	0.29	8.5	9	8	100	30
ZN/BR_2 EV 100	30	13300	0.31	6	4	8	100	30
NI/ZN EV 150	51	15500	0.27	8.5	9	8	150	30
ZN/CL_2 EV 250	28	19700	0.32	6	4	8	250	30
FE/AIR EV 250	25	16100	0.29	6	6	8	250	30
LI/FES EV 250	41	19300	0.29	7.5	9	8	250	30
NA/S EV 250	50	18400	0.29	6.5	5	8	250	30

Table 6-5. Advanced Vehicle Rankings: Most Preferred of Electric Vehicles - Multiplicative Model

	BATTERY/VEHICLE									
GROUP	PB/ACID EV 100	BIPOLAR EV 100	NI/FE EV 100	NI/ZN EV 100	ZN/BR_2 EV 100	NI/ZN EV 150	ZN/CI_2 EV 250	FE/AIR EV 250	LI/FES EV 250	NA/S EV 250
AV FLEET	2	1	6	4	10	3	9	8	5	7
AUTOMOTIVE RESEARCH	2	1	6	3	9	4	10	8	7	5
AUTOMOTIVE CORPORATE	2	1	6	4	10	3	9	8	5	7
AUTOMOTIVE CONSUMER/ MARKET RESEARCH	6	1	8	4	10	5	9	7	2-3	3-4
DOE/JPL	2	1	6	3-5	10	4-5	9	8	3-4	7
ALTERNATIVE FUEL SUPPLIERS	4	1	6-8	3	10	2	9	7	5	6-7
UTILITY RESEARCH (EPRI)	2	1	6-7	3	9	4	10	8	5	7
ELECTRIC UTILITIES	4-6	1-2	8	5-7	10	3	9	5-6	1-2	4-5

Table 6-6. Advanced Vehicle Rankings: Most Preferred of Electric Vehicles - Additive Model

	BATTERY/VEHICLE									
GROUP	PB/ACID EV 100	BIPOLAR EV 100	NI/FE EV 100	NI/ZN EV 100	ZN/BR_2 EV 100	NI/ZN EV 150	ZN/CL_2 EV 250	FE/AIR EV 250	LI/FES EV 250	NA/S EV 250
AV FLEET	2	1	6	4	10	3	9	8	5	7
AUTOMOTIVE RESEARCH	2	1	6	3	9	4	10	8	5	7
AUTOMOTIVE CORPORATE	2	1	6	4	10	3	9	8	5	7
AUTOMOTIVE CONSUMER/ MARKET RESEARCH	5	1	7	2-3	10	3-4	9	8	2-4	6
DOE/JPL	2	1	6	3	10	3-4	9	8	5	7
ALTERNATIVE FUEL SUPPLIERS	5	1	7	4	10	2-3	9	8	2-3	5-6
UTILITY RESEARCH (EPRI)	2	1	7	3	10	4	9	8	5	6
ELECTRIC UTILITIES	4	1	8	5	10	3	9	7	2	6

Notwithstanding the differences among the groups, the rankings for these ten EVs are summarized in Table 6-7. The bipolar 100-mile EV ranked highest due to lower initial and life-cycle costs and to higher safety/maintainability ratings and relative fuel economy. Following the bipolar EV are four vehicles whose ranking varies somewhat among the groups: the lead-acid 100-mile, nickel-zinc 100- and 150-mile, and the lithium-iron sulfide 250-mile EV. These vehicles comprise the top-ranked five of the EVs.

Next ranked were the sodium-sulfur and nickel-iron 250-mile EVs while lowest-ranked were the iron-air 250-mile, zinc-chlorine 250-mile and zinc-bromine 250-mile EVs. Low-ranked vehicles were hampered by high initial costs and low fuel economy, maintainability, and safety ratings.

H. MOST PREFERRED OF THE 250-MILE-RANGE VEHICLES

The rankings described in Section VI-E were used to identify the most preferred of the 250-mile range EVs. The top three of these were the lithium-iron sulfide, sodium-sulfur, and iron-air 250-mile EVs. The baseline ICE and fuel-cell vehicle ranked ahead of these three EVs.

Similarly, Section VI-F discusses rankings of 250-mile HVs and a baseline ICE. The top-ranked HVs are: bipolar, lead-acid, nickel-zinc, nickel-iron, and lithium-iron sulfide.

Table 6-7. Ranking for Most Preferred of Each Technology for Five-Passenger Electric Vehicles

MOST PREFERRED	BIPOLAR 100
↓	LEAD-ACID 100
	NICKEL-ZINC 100 AND NICKEL-ZINC 150
	LITHIUM-METAL SULFIDE 250
	SODIUM-SULFUR 250 NICKEL-IRON 250
	IRON-AIR 250
	ZINC-CHLORINE 250
LEAST PREFERRED	ZINC-BROMINE 250

The attribute data for these ten vehicles (three EVs, five HVs, one baseline ICE, and one fuel-cell vehicle) are given in Table 6-8. Comparing these data with the attribute-state ranges of Table 5-7 reveals that the greatest variation of the attribute data with regard to the ranges occurs for relative fuel economy, initial cost, safety, and maximum refuel time. The initial cost difference between the baseline ICE and the other nine vehicles is substantial. Also, the maximum refuel time for the EVs of 8 hours is at the extreme end of the range from the maximum refuel time of 10 minutes for the other vehicles.

Rankings were calculated for these ten 250-mile-range vehicles using both the multiplicative and additive models given in Section II. The rankings for the multiplicative model are contained in Table 6-9 while rankings for the additive model are contained in Table 6-10. Again, as in the previous comparison in Section VI-G, there is good agreement between the rankings obtained with the additive and multiplicative models. Differences in rankings between the two models is, at most, one place.

The comparison of rankings among the groups is close except for two vehicles: the baseline ICE and the lead-acid HV. These differences are due to the variation in importance among the groups for the initial cost and safety attributes as shown in Table 5-4.

Despite the differences in group rankings just noticed, the rankings for these ten vehicles are summarized in Table 6-11. The bipolar HV is clearly highest-ranked due to its high fuel-economy, maintainability, and safety ratings. It is difficult to separate the next-ranked vehicles due to variation among the group rankings. These three are the lead-acid and nickel-zinc HVs and the baseline ICE. The lead-acid and nickel-zinc HVs benefited from high safety and maintainability ratings while the baseline ICE was helped by low initial cost. The lithium-iron sulfide HV ranked fifth, followed by the closely ranked nickel-iron HV, the fuel-cell, and the lithium-iron sulfide EV. Lowest in the rankings were the sodium sulfur and iron-air EVs. The EV rankings were adversely affected by the high maximum refuel time, high initial costs, and in the case of the iron-air EV, low relative fuel economy.

I. MOST PREFERRED OF THE ADVANCED VEHICLES

The advanced vehicles to be considered for most-preferred ranking were drawn from the five top-ranked EVs identified in Section VI-G and the four highest-ranked HVs and the baseline ICE identified in Section VI-H. The ranking of these ten vehicles was targeted to answer the question: How do the top-ranked EVs compare with the top-ranked HVs and baseline ICE? The five EVs included here were the lead-acid 100-mile, bipolar 100-mile, nickel-zinc 150-mile, the lithium-iron sulfide 250-mile, and sodium-sulfur 250-mile. The 250-mile HVs included were the lead-acid, bipolar, nickel-zinc, and the lithium-iron sulfide. The tenth vehicle was the baseline ICE evaluated for a 250-mile range driving cycle.

The attribute data for these ten vehicles are given in Table 6-12. Comparing these data with the attribute-state ranges of Table 5-7 reveals that the greatest variation of the attribute data with regard to the ranges occurs

Table 6-8. Attribute Data for Rankings Involving Most Preferred of 250-mi-Range Vehicles

VEHICLE	RELATIVE FUEL ECON. mi/gal	INITIAL COST, 1982 $	LCC, $/mi 1982 $	MAINTAIN-ABILITY	SAFETY	MAXIMUM REFUEL TIME, h	UNREFUELED RANGE, mi	MAXIMUM START TIME, s
BASE ICE 250	49	7200	0.23	6	6	0.17	250	30
FE/AIR EV 250	25	16100	0.29	6	6	8	250	30
LI/FES EV 250	41	19300	0.29	7.5	9	8	250	30
NA/S EV 250	50	18300	0.29	6.5	5	8	250	30
PB/ACID HV 250	48	14900	0.29	7	10	0.17	250	30
BIPOLAR HV 250	61	12700	0.25	8	10	0.17	250	30
NI/ZN HV 250	51	13700	0.28	7.5	9	0.17	250	30
LI/FES HV 250	43	15500	0.30	6.5	9	0.17	250	30
NI/FE HV 250	39	16300	0.29	6.5	7	0.17	250	30
FUEL CELL	58	17600	0.31	6	6	0.17	250	30

Table 6-9. Advanced Vehicle Rankings: Most Preferred of 250-mi-Range Vehicles - Multiplicative Model

GROUP	BATTERY/VEHICLE									
	BASE ICE 250	FE/AIR EV 250	LI/FES EV 250	NA/S EV 250	PB/ACID HV 250	BIPOLAR HV 250	NI/ZN HV 250	LI/FES HV 250	NI/FE HV 250	FUEL CELL
AV FLEET	2-3	10	7-8	9	2-3	1	4	5	6	7-8
AUTOMOTIVE RESEARCH	3-4	10	7-8	9	2	1	3-4	5	6	7-8
AUTOMOTIVE CORPORATE	5	10	6	9	2	1	3	4	7	8
AUTOMOTIVE CONSUMER/ MARKET RESEARCH	1	10	8	9	4	2	3	5	7	6
DOE/JPL	4	10	6-7	9	2	1	3	5	6-7	8
ALTERNATIVE FUEL SUPPLIERS	1-2	10	8	9	4	1-2	3	5	7	6
UTILITY RESEARCH (EPRI)	3	10	6	9	2	1	4	5	7	8
ELECTRIC UTILITIES	2-3	10	7-8	9	2-3	1-2	4	5	6	7-8

Table 6-10. Advanced Vehicle Rankings: Most Preferred of 250-mi-Range Vehicles - Additive Model

	BATTERY/VEHICLE									
GROUP	BASE ICE 250	FE/AIR EV 250	LI/FES EV 250	NA/S EV 250	PB/ACID HV 250	BIPOLAR HV 250	NI/ZN HV 250	LI/FES HV 250	NI/FE HV 250	FUEL CELL
AV FLEET	2	10	8	9	4	1	3	5	6	7
AUTOMOTIVE RESEARCH	3-4	10	8	9	2	1	3-4	5	6	7
AUTOMOTIVE CORPORATE	4-5	10	6	9	2	1	3	4	7	8
AUTOMOTIVE CONSUMER/ MARKET RESEARCH	2	10	8	9	4	1	3	5	7	6
DOE/JPL	4	10	7	9	2	1	3	5	6	8
ALTERNATIVE FUEL SUPPLIERS	1-2	10	8	9	4	1-2	3	5	6-7	6-7
UTILITY RESEARCH (EPRI)	3-4	10	6-7	9	2	1	3-4	5	6-7	8
ELECTRIC UTILITIES	3-4	10	8	9	2	1	4	5	6	7

Table 6-11. Ranking for Most Preferred of all 250-mi-Range Vehicles

MOST PREFERRED	
	BIPOLAR HV
	LEAD-ACID HV BASELINE ICE NICKEL-ZINC HV
	LITHIUM-IRON SULFIDE HV
	NICKEL-IRON HV FUEL CELL LITHIUM-IRON SULFIDE EV
	SODIUM-SULFUR EV
	IRON-AIR EV
LEAST PREFERRED	

for initial cost, maintainability, safety, maximum refuel time, and unrefueled range. The initial-cost difference between the baseline ICE and the other nine vehicles is substantial. The maximum refuel time of 8 hours for the EVs contrasts sharply with the 10-minute refuel time of the other vehicles. The 100-mile range for two of the EVs is far from the 250-mile range of seven of the vehicles considered here.

Again, rankings were calculated for these ten vehicles with both the multiplicative and additive models given in Section II. The rankings for the multiplicative model are shown in Table 6-13 while rankings for the additive model are contained in Table 6-14. As in earlier comparisons, agreement between the rankings obtained with the multiplicative and additive models is good. Differences are within one or two places.

The comparison of rankings among the groups is close for the highest-rated bipolar HV and for the lowest-ranked nickel-zinc 150-mile EV, lithium-iron sulfide 250-mile EV, and sodium-sulfur 250-mile EV. Variations among the groups for the baseline ICE and the lead-acid and bipolar 100-mile EVs vary as much as six places. The different emphasis on the attributes of initial cost and safety account for much of this variation. Groups with greater emphasis on initial cost rank the baseline ICE high while those with greater emphasis on safety rank the bipolar and lead-acid 100-mile EVs higher. The widest differences in group rankings are for the automotive corporate group.

Table 6-12. Attribute Data for the Ten Most-Preferred Vehicles

VEHICLE	RELATIVE FUEL ECON, mi/gal	INITIAL COST, 1982 $	LCC, $/mi 1982 $	MAINTAIN-ABILITY	SAFETY	MAXIMUM REFUEL TIME, h	UNREFUELED RANGE, mi	MAXIMUM START TIME, s
BASE ICE 250	49	7200	0.23	6	6	0.17	250	30
PB/ACID HV 250	48	14900	0.29	7	10	0.17	250	30
BIPOLAR HV 250	61	12700	0.25	8	10	0.17	250	30
NI/ZN HV 250	51	13700	0.28	7.5	9	0.17	250	30
LI/FES HV 250	43	15500	0.30	6.5	9	0.17	250	30
PB/ACID EV 100	52	13800	0.28	8	10	8	100	30
BIPOLAR EV 100	68	12100	0.25	9	10	8	100	30
NI/ZN EV 150	51	15500	0.27	8.5	9	8	150	30
LI/FES EV 250	41	19300	0.29	7.5	9	8	250	30
NA/S EV 250	50	18300	0.29	6.5	5	8	250	30

Table 6-13. Advanced Vehicle Rankings: Most Preferred of Electric Vehicles and Best of Hybrid Vehicles, Baseline, and Fuel Cell - Multiplicative Model

	BATTERY/VEHICLE									
GROUP	BASE ICE 250	PB/ACID HV 250	BIPOLAR HV 250	NI/ZN HV 250	LI/FES HV 250	PB/ACID EV 100	BIPOLAR EV 100	NI/ZN EV 150	LI/FES EV 250	NA/S EV 250
AV FLEET	2-3	2-3	1	4	6	7	5	8	9	10
AUTOMOTIVE RESEARCH	4	2	1	5	7	6	3	8	9	10
AUTOMOTIVE CORPORATE	7	3	1-2	5	6	4	1-2	8	9	10
AUTOMOTIVE CONSUMER/ MARKET RESEARCH	1	4	2	3	5	10	6	9	7	8
DOE/JPL	5	2	1	3	6	7	4	9	8	10
ALTERNATIVE FUEL SUPPLIERS	1	4	2	3	5	8	6	7	9	10
UTILITY RESEARCH (EPRI)	4	3	1	6	7	5	2	8	9	10
ELECTRIC UTILITIES	2	3	1	4	5	9-10	7	8	6	9-10

Table 6-14. Advanced Vehicle Rankings: Most Preferred of Electric Vehicles and of Hybrid Vehicles, Baseline, and Fuel Cell - Additive Model

	BATTERY/VEHICLE									
GROUP	BASE ICE 250	PB/ACID HV 250	BIPOLAR HV 250	NI/ZN HV 250	LI/FES HV 250	PB/ACID EV 100	BIPOLAR EV 100	NI/ZN EV 150	LI/FES EV 250	NA/S EV250
AV FLEET	2	4	1	3	5	7	6	8	9	10
AUTOMOTIVE RESEARCH	3-4	2	1	3-4	6	7	5	8	9	10
AUTOMOTIVE CORPORATE	7	3	1	4	6	5	2	8	9	10
AUTOMOTIVE CONSUMER/ MARKET RESEARCH	2	4	1	3	5	9	6	7-8	7-8	10
DOE/JPL	4	2	1	3	6	7	5	8	9	10
ALTERNATIVE FUEL SUPPLIERS	1	4	2	3	5	9	6	7-8	7-8	10
UTILITY RESEARCH (EPRI)	4	2	1	5	7	6	3	8	7	10
ELECTRIC UTILITIES	3	2	1	4	5	9	6	8	9	10

Despite the variation in group rankings, an effort is made to summarize these group rankings for the ten vehicles in Table 6-15. Given the disparity in group rankings, one cannot attach great significance to one or two place differences in ranking. In general, the HVs and baseline ICE rank higher than the EVs, with the exception of the bipolar 100-mile EV ranking ahead of the lithium-iron sulfide HV (for five of the eight groups). The bipolar HV seems to be the overall preference leader with the baseline ICE, lead-acid HV, nickel-zinc HV, bipolar 100-mile EV, and lithium-iron sulfide HV showing promise. Trailing are the lead-acid 100-mile, nickel-zinc 150-mile, lithium-iron sulfide 250-mile, and sodium-sulfur 250-mile EVs. All of the EVs ranking were adversely affected by their long maximum refuel time. Also, the 100-mile EVs are less preferred due to their relatively short range while the 250-mile EVs suffer from high initial cost.

J. RANKING SUMMARY AND ANALYSIS

For most groups interviewed, the top-ranked EVs are less-preferred than the baseline ICE and the top-ranked HVs. Only the automotive corporate and electric utilities researchers ranked a top-ranked EV, the bipolar 100-mile, over most HVs. For the other groups, the top-ranked EVs--the bipolar 100-mile, and nickel-zinc 150-mile (or nickel-zinc 100-mile) and lithium-iron sulfide 250-mile--are less preferred than the top-ranked HVs and the baseline ICE.

Table 6-15. Ranking of Most-Preferred Five-Passenger Vehicles

	TECHNOLOGY	CONFIGURATION	
MOST PREFERRED	BIPOLAR	HV	(250-MI RANGE)
	BASELINE	ICE	(250-MI-RANGE CYCLE)
	LEAD-ACID	HV	(250-MI RANGE)
	NICKEL-ZINC	HV	(250-MI RANGE)
	BIPOLAR	EV	(100-MI RANGE)
	LITHIUM-IRON SULFIDE	HV	(250-MI RANGE)
	LEAD-ACID	EV	(100-MI RANGE)
	NICKEL-ZINC	EV	(150-MI RANGE)
	LITHIUM-IRON SULFIDE	EV	(250-MI RANGE)
LEAST PREFERRED	SODIUM-SULFUR	EV	(250-MI RANGE)

The top-ranked HVs are those using bipolar, lead-acid, nickel-zinc, and lithium-iron sulfide battery technologies.

It is worth looking into why two of the groups rank the leading EVs higher than do the other groups. To do this requires looking at both the attribute-state data of Table 6-12 and a summary of the median additive attribute weights for each group, summarized in Table 6-16. The additive attribute weights were calculated by dividing the multiplicative scaling constants by the sum of the scaling constants.

The two attributes that adversely affected the bipolar 100-mile EV and nickel-zinc 150-mile EV are the maximum refuel time and unrefueled range. The two groups that ranked the top EVs high, the automotive corporate and electric utilities researchers, have relatively low additive weights for those two attributes. When the EV range is extended to 250 miles, the top- ranked EVs with the lithium-iron sulfide and sodium-sulfur battery technologies have too high an initial cost ($19,300 and $18,300, respectively) to compete with the top-ranked HVs.

Looking at all of the foregoing rankings, the most promising battery technologies for EVs seem to be bipolar, lead-acid, nickel-zinc, lithium-iron sulfide, nickel-iron, and sodium-sulfur. These same battery technologies also led to the top-ranked HVs.

The consistently lowest-ranking battery technologies were iron-air, aluminum-air, zinc-chlorine and zinc-bromine, all of which compared poorly with other battery technologies in terms of fuel economy, maintainability, and safety.

K. CRITIQUE OF MULTIATTRIBUTE DECISION-ANALYSIS METHODOLOGY

The multiattribute decision-analysis methodology was successful in 39 out of 40 interviews in ranking all the alternative vehicles. The group-decision rules were capable of aggregating preferences by groups, and, in general, the three group-decision rules were in agreement.

The multiattribute decision analysis was a deterministic analysis, as contrasted with a probabilistic analysis and so did not completely reveal the technical experts' opinion as to the attribute states of the alternative vehicles. A better analysis could have been undertaken if the attribute states had been estimated probabilistically. Either a discrete probability tree or a Monte Carlo simulation model, using subjectively estimated cumulative probability distributions for the attribute states of the alternative vehicles, would have been sufficient data for a probabilistic analysis. The present analysis does not incorporate the uncertainties in the attribute state estimates.

The interview times could have been shortened if only three-point rather than five-point estimates had been made of the attribute utility functions. With the worst-state and the best-state used for two of the three points, questions for only one attribute utility value need be asked in the interviews. Comparison of Table 6-4 and Table 6-7 of Reference 1 shows that only

Table 6-16. Median Additive Attribute Weights

GROUP	FUEL ECONOMY	INITIAL COST	LIFE-CYCLE COST	MAINTAIN-ABILITY	SAFETY	MAXIMUM REFUEL TIME	UNREFUELED RANGE	MAXIMUM START TIME
	ATTRIBUTES							
AV FLEET	0.104	0.157	0.178	0.122	0.133	0.099	0.100	0.107
AUTOMOTIVE RESEARCH	0.106	0.178	0.109	0.115	0.229	0.090	0.075	0.098
AUTOMOTIVE CORPORATE	0.145	0.137	0.122	0.147	0.201	0.074	0.089	0.085
AUTO. CONSUMER/ MARKET RESEARCH	0.136	0.189	0.133	0.110	0.073	0.114	0.127	0.118
DOE/JPL	0.096	0.142	0.117	0.132	0.233	0.091	0.099	0.090
ALT. FUEL SUPPLIERS	0.138	0.165	0.137	0.126	0.118	0.099	0.116	0.101
ELEC. UTIL. RESEARCH	0.102	0.160	0.135	0.170	0.195	0.069	0.081	0.088
ELECTRIC UTILITIES	0.085	0.112	0.156	0.121	0.163	0.087	0.183	0.093
RANGE	0.085-0.145	0.112-0.189	0.109-0.178	0.110-0.170	0.073-0.233	0.069-0.114	0.075-0.183	0.085-0.118

minor (one-place at most) differences in the rankings would have resulted in the group-decision rules. Because continuity and monotonicity of preferences can be assumed for the attribute states, an attribute utility function of the "constant risk-aversion" form

$$u(x) = a + be^{cx}$$

would have sufficed. Given the high premium for short interview times, it is recommended that in the future, unless there is strong reason to believe that the utility function is not represented by such a function with sufficient accuracy, the attribute utility functions be derived from three-point estimates.

The attribute ranges could have been compressed, and one of the attributes (maximum start-up time) could have been eliminated if the alternative vehicle states had been determined prior to conducting the interviews. This would have made the assessment process easier for the interviewees, resulted in better assessments, and also would have shortened the interview time. It was difficult for some, and impossible for others, of the interviewees to assess gambles with respect to the set of attributes at their worst states. Had the alternative-vehicle states been determined in advance, the attribute worst states could have been made more desirable. It is highly recommended, in future multiattribute-decision analyses, that the system states be determined before the interviews are conducted. This will also preclude the unfortunate situation in which the system states are ultimately determined to lie outside the range of the assessed attribute states.

SECTION VII

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Part Two
Aftermarket Analyses

M.A. Gyamfi

SECTION I

METHANOL AVAILABILITY

A. INTRODUCTION

The aftermarket analyses are narrowly defined for the purposes of the Advanced Vehicle (AV) Assessment. The systems analyses required assumptions of liquid-fuel and electricity prices as well as estimates of their availability; this section of the Aftermarket Analyses addresses those issues. The evaluation of nonpetroleum fuel availability is limited to methanol obtained from coal and natural gas. The assessment of electricity availability includes various sources that the utility industry anticipates will be accessible in the next 2 decades.

Several studies have been conducted regarding nonpetroleum vehicle fuels (References 1-1, 1-2, 1-3, and 1-4). Methanol seems to be the fuel of choice in the long run because it is producible from coal (Reference 1-5). The production technology is available and is economical relative to other synfuel processes. The heat-engine assessment of the AV Subsystem Technology Assessment indicates that of four candidate fuels examined (methanol, ethanol, natural gas, and ammonia), methanol is the most attractive. Therefore, methanol was chosen as the most likely nonpetroleum fuel and is the primary subject of this report. This assessment includes an analysis of methanol-production technology, cost, transportation, storage, future supply of methanol, and scenarios for future vehicular methanol supply and demand.

B. PRESENT SUPPLY AND DEMAND

Free-World methanol production of 12.2 billion liters (3.22 billion gallons) in 1981 rose by 1.1 billion liters (0.3 billion gallons) to 13.3 billion liters (3.52 billion gallons) in the first quarter of 1982 (Table 1-1). The United States produced approximately one-third of the total amount from natural gas. Methanol production in the United States grew at an average annual rate of 7.4% from 1965 to 1981 and 5.8% during the 1978 to 1982 time period. Since 1979 nameplate capacity has been in the 4.31 to 5.86 billion liter (1.14 to 1.55 billion gallon) range with production levels of 4.05 to 4.77 billion liters (1.07 to 1.26 billion gallons) during the same period, indicating a plant utilization factor of 80 to 90% (References 1-6, 1-7, and 1-8). The historical perspective is shown in Figure 1-1.

Methanol is used in a number of developing applications in the United States as shown in Figure 1-2, which depicts the 1979 demand. The main use of methanol is in the production of formaldehyde, which constituted approximately 36% of methanol production in 1980. This percentage dropped from 42.5% in 1979, perhaps due to the housing market decline, which uses products from formaldehyde. Methanol is also used as a feedstock for the manufacture of resin, glue, and plastic. During the 1979 to 1982 period exports averaged 265 million liters (70 million gallons), and imports were approximately

Table 1-1. Free World Methanol Balance from 1981 to 1987 (Source: Adapted from California Methanol Assessment, Reference 1-10)

Production and Consumption	Production and consumption,[a] billion gallons						
	1981	1982	1983	1984	1985	1986	1987
New cumulative production	NA[b]	0.3	0.7	1.2	1.86	2.43	2.75
Effective production	3.22	3.52	3.92	4.42	5.08	5.64	5.98
Consumption	2.91	3.47	3.74	3.97	4.17	4.3	4.47

List of New Capacity

Year	Country	Company	Capacity, million gal/yr	Cumulative capacity, billion gal/yr	Cumulative production, billion gal/yr
1982	Canada	Alberta	130	0.46	0.3
		Ocelot	130		
		Celanese	200		
1983	USA	Arco	190		
		Getty	100		
	Taiwan	CPDC	35	0.7	0.7
	Trinidad	NEC	110		
1984	S. Arabia	Sabic/Japan	220		
	Libya	NMC	110		
	N Zealand	Petralgas	130	1.56	1.2
	Indonesia	Pertamina	200		
1985	UK	ICI	270		
	S. Arabia	Sabic/Celanese	220		
	Mexico	Pemex	270	2.42	1.86
	Bahrain	GPIC	110		
1986	Malaysia	Petronas	100		
	Malaysia	(Borden)	110		
	Holland	Methanor	140		
	Argentina	Huarpes	200	3.09	2.43
	Bangladesh	Beximco	110		
1987	Germany	Shell	130	3.43	2.76
	N. Zealand	NZ/Mobil	200		
1988	USA	TVA	330	3.93	3.26
	Norway	Dyno	170		

[a]Multiply billion gallons by 3.785 to determine billion liters.

[b]Not applicable.

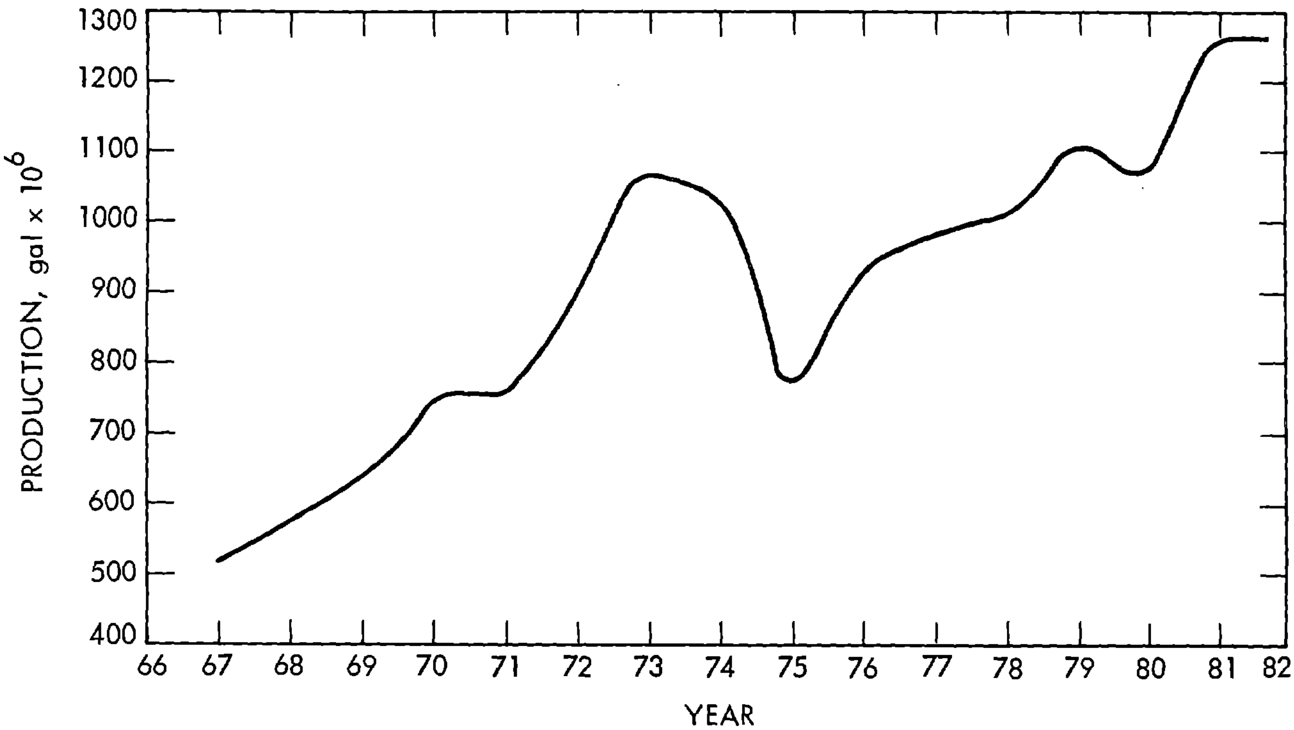

Figure 1-1. Historical Methanol Production in the United States

151.4 million liters (40 million gallons) per year. Note that only 8% of the U.S. production was used as a gasoline blend for vehicle fuel in 1979.

C. FUTURE SUPPLY AND DEMAND

Forecasters disagree on methanol supply and demand forecast for the future. British Sulphur Corporation (London) predicts there will be a glut by 1985 while Chem Systems, Inc. (New York) predicts a worldwide shortage by 1990. One way to gauge the market is to assess the plans for production. Planned production facilities to produce methanol from natural gas are scattered throughout the world (see Table 1-1). As can be seen in this table, new cumulative capacity is expected to rise from 1.74 billion liters (0.46 billion gallons) in 1982 to 13.0 billion liters (3.43 billion gallons) in 1987. The resulting new cumulative production is expected to be 1.1 billion liters (0.3 billion gallons) in 1982, increasing to 10.4 billion liters (2.76 billion gallons) in 1987. The total effective production is expected to be 22.6 billion liters (5.98 billion gallons) in 1987.

Data Resources Incorporated (DRI) projects the supply of methanol to be 5.7 billion liters (1.5 billion gallons) in 1985 and 6.8 billion liters (1.8 billion gallons) in 1990, an average annual rate of growth of 3.7% (personal communication with DRI, Los Angeles Office, May 1982; also see Table 1-2.) This is slightly lower than projections made by Conoco.

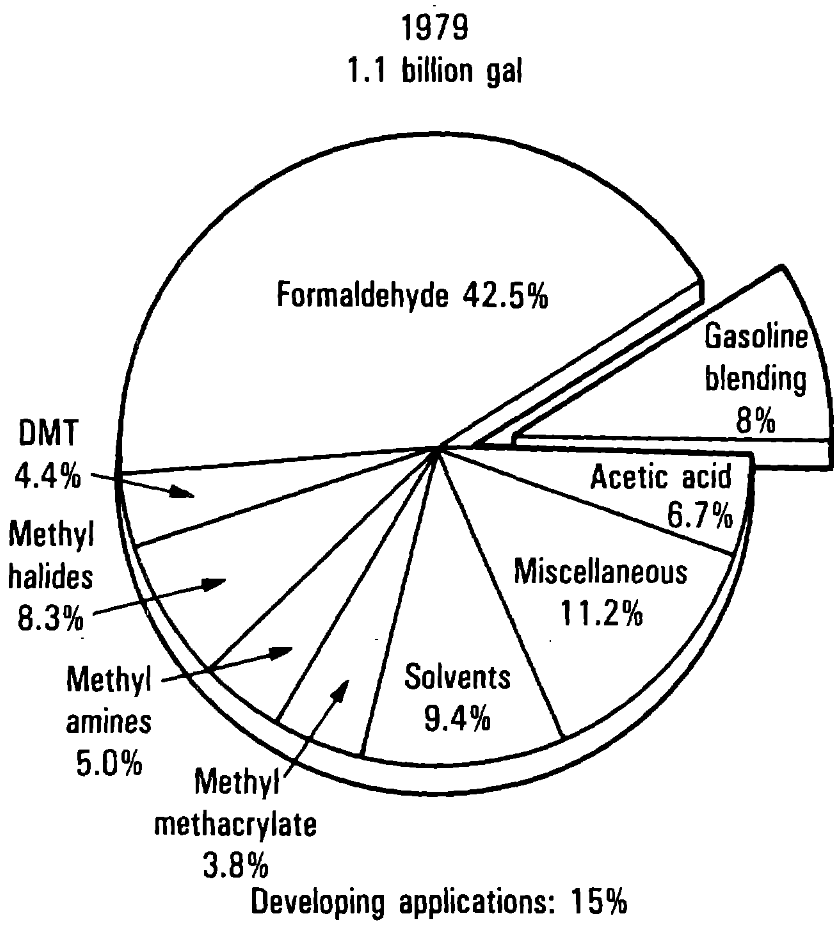

Figure 1-2. U.S. Methanol Demand in 1979 (Source: Reference 1-9)

On the demand side, the DuPont Company predicts a 9% average annual increase over the next several years (see Reference 1-9). Figure 1-3 shows the Chem Systems projections for methanol demand in 1990. Note that the demand for transportation (i.e., gasoline blending and MTBE, an additive) is expected to be 23.5% of the total, second to formaldehyde. Based on the total amount of production, the projections do not include a large demand from the transportation sector consistent with petroleum scarcity.

D. POTENTIAL VEHICULAR APPLICATIONS

At the present time methanol is used as an octane-enhancing blending agent for unleaded gasoline. The projection of future vehicular methanol demand requires estimates of the mix of the fleet of cars, fuel economy, and distance driven. The AV Assessment includes two-, four-, and five-passenger cars designed to use methanol as fuel. These cars were projected to get 10 to 15 km/l (24 to 35 mi/gal) on methanol. The assumption that the fleet average fuel economy is 11 km/l (26 mi/gal) and that each car will be driven an

Table 1-2. United States Methanol Production Capacity[a] (Source: Adapted from California Methanol Assessment, Reference 1-10)

Producer	1980	1981	1982	1983	1984	1985	1986	1987	1988
Air Products Pensacola, LA	50	50	50	50	50	60	60	60	60
Allemania Chem. Plaquemine, LA	100	130	130	130	130	130	130	130	130
Arco Chem. Gulf Coast	NA[b]	NA	NA	190	190	190	190	190	190
Borden, Inc. Geisman, LA	160	180	180	180	180	180	180	180	180
Celanese Corp. Bishop, TX Clear Lake, TX	375	385	385	385	385	385	385	385	385
Du Pont Beaumont, TX Clear Lake, TX Dear Park, TX	340	540	540	565	565	565	565	565	565
Eastman Chem.	NA	NA	NA	NA	50	50	50	50	50
Georgia Pacific Plaquemine, LA	120	125	125	125	125	125	125	125	125
Getty Oil	NA	NA	NA	100	100	100	100	100	100
Hercofine Plaquemine, LA	100	100	100	100	100	100	100	100	100
Monsanto Texas City, TX	100	100	100	100	100	100	100	100	100
Rohm and Hass Dear Park, TX	22	22	22	22	22	22	22	22	22
Tenneco, Inc. Houston, TX	80	82	130	130	130	130	130	130	130
Valley Nitrogen Hercules, GA	8	8	8	8	8	8	8	8	8
Total U.S.	1,455	1,722	1,770	2,085	2,135	2,145	2,145	2,145	2,145
Other Free World	2,280	2,280	2,740	2,885	3,545	4,415	5,085	5,415	5,585
Total	3,735	4,002	4,510	4,970	5,680	6,560	7,231	7,560	7,730

[a]In million gallons. To determine million liters multiply million gallons by 3.785.

[b]Not applicable.

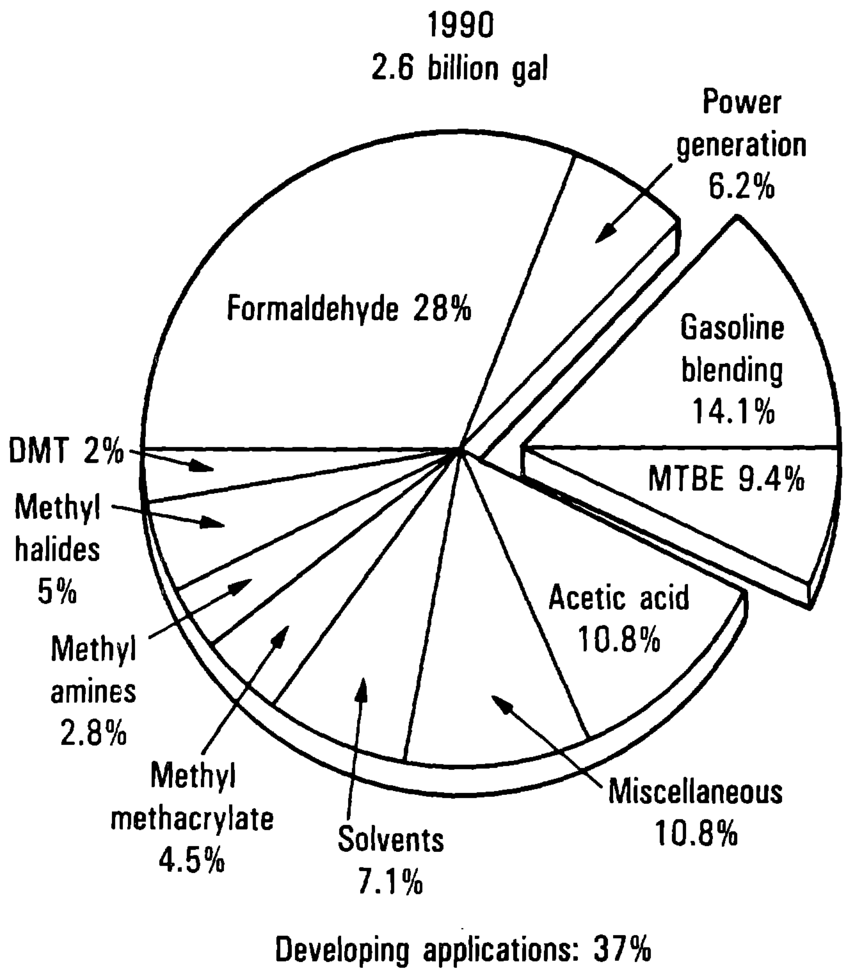

Figure 1-3. United States Methanol Demand in 1990 (Source: see Reference 1-9)

average of 16,000 km/yr (10,000 mi/yr) implies that the demand for vehicular methanol could be estimated with assumptions of the market penetration and the fleet size.

Three scenarios of vehicle demand were assumed. The first scenario assumed that 25% of the fleet used methanol, which translated to 37.5 million vehicles. If each vehicle traveled 16,000 km (10,000 mi) in a year, 54.6 billion liters (14.4 billion gallons) of methanol would be required. The second scenario assumed 50% of the fleet would use methanol. With identical assumptions, methanol demand would be 109.2 billion liters (28.8 billion gallons). In the third scenario, the entire fleet used methanol, and the demand would be 218.4 billion liters (57.6 billion gallons).

The future supply of vehicular methanol will depend on the demand. At the present time an insignificant amount of vehicular methanol is produced for use in test vehicles and also for fleets such as that acquired by Bank of America in California. The United States is currently producing 4 to 5 billion liters from natural gas. To satisfy the demand projections in any of the three scenarios, significant investment will be needed for plants that produce vehicular methanol fuel.

Table 1-3 summarizes the significant impact on the fuel-supply industry if the transportation scenarios were realized. Note that, if only 25% of the fleet were to use methanol, production would have to increase by an order of magnitude from the present levels.

E. AVAILABILITY OF FEEDSTOCK

1. Coal

Data available from a U.S. Geological Survey show that the United States has sufficient coal resources to last for over 400 years at today's consumption levels (Reference 1-11). In 1979 the United States produced 781 million short tons of coal, about 19% of world total of 4,123 million short tons, as shown in Figure 1-4.

2. Natural Gas

Natural gas resources are found both onshore and offshore. In the United States, newly found gas resources are primarily in remote areas, and proposals are being made to tap these resources. Table 1-4 summarizes these resources.

F. METHANOL-PRODUCTION TECHNOLOGY

Several processes are available for producing methanol from coal, natural gas, and other feedstocks. Most of these processes are at laboratory or demonstration stages, while few are proven commercially. The production technology, for the purposes of this study, must be commercially available prior to 1990 to enable production beyond 1990. In the following paragraphs, methanol production from coal and natural-gas feedstocks are discussed, together with reviews of methanol production undertaken in other studies.

Table 1-3. Methanol Production Increase Required to Meet Vehicular Demand

Scenario, % fleet	Demand, billion liters	Production Increase, %
25	54.6	1100
50	109.2	2200
100	214.6	4400

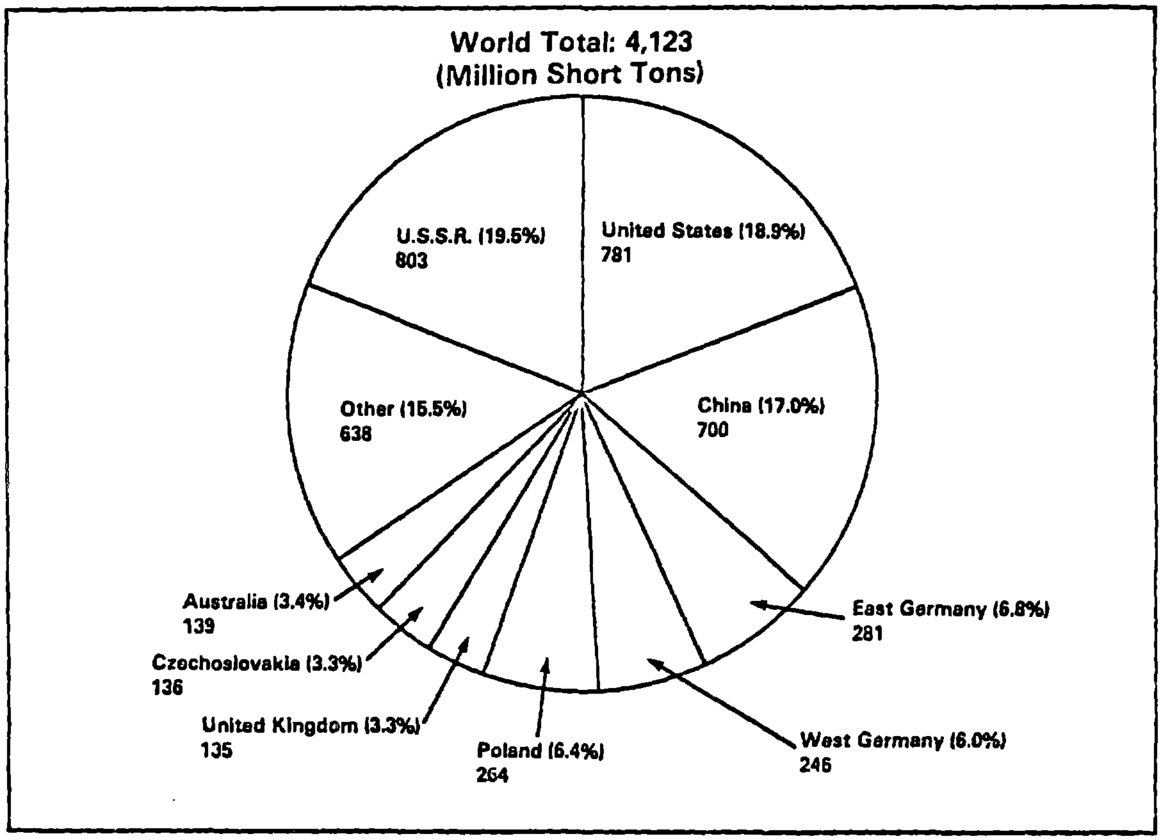

Figure 1-4. International Coal Production in 1979
(Source: see Reference 1-11)

1. Coal Conversion

The conversion of coal to methanol requires two processes: coal gasification and methanol synthesis. The candidate commercial coal gasification processes being considered in various studies are the Winkler, Koppers-Totzck, Lurgi, and the Texaco Partial Oxidation. Winkler and Koppers-Totzck are both low pressure (close to atmospheric) and require compression of the synthesis gas; therefore, these two processes are not considered promising. The Lurgi process, although commercially proven, produces large amounts of other hydrocarbons, and additional processing steps are required to convert the syngas to feedstock required by the methanol converter. The Texaco partial-oxidation process has been commercially demonstrated with other feedstock such as natural gas and petroleum coke. Texaco has operated a 15-ton/day pilot plant gasifier at their facility in El Monte, California, for a number of years, extending back to the 1950s (see Reference 1-10). This process was chosen for the purposes of this study.

For commercial methanol synthesis, the ICI and Lurgi processes were considered. Both exhibit the same performance and also meet the 1990 time period for commercialization. The Lurgi process was selected over ICI, primarily because of its successful history of operation. A plant for producing methanol from coal with this two-step process was chosen, based on

Table 1-4. Estimated Undiscovered Recoverable Natural Gas Resources in 1980[a]

Region	Statistical mean[b]	Estimated range[c]
On-shore		
Alaska	36.6	19.8 - 62.3
Pacific Coast	14.6	8.2 - 24.9
Colorado Plateau, Basin, and Range	90.1	53.5 - 142.4
Rocky Mountains and Northern Great Plains	45.8	29.6 - 69.0
West Texas and Eastern New Mexico	42.8	22.4 - 75.2
Gulf Coast	124.4	56.5 - 249.1
Mid Continent	44.5	22.9 - 80.8
Michigan Basin	5.1	1.8 - 10.9
Eastern Interior	2.7	1.2 - 5.0
Appalachians	20.1	6.4 - 45.8
Atlantic Coast	0.1	0.1 - 0.4
Total Onshore	426.9	322.5 - 567.9
Off-shore		
Alaska[d]	64.6	33.3 - 109.6
Pacific Coast	6.9	3.7 - 13.6
Gulf of Mexico	71.9	41.7 - 114.2
Atlantic Coast	23.6	9.2 - 42.8
Total Offshore	167.0	177.4 - 230.6
Total United States	593.9	474.6 - 739.3

[a]Source: See Reference 1-11. Units are in trillion cubic feet.

[b]The calculated mean from the probability curve, using the Monte Carlo technique.

[c]The low value of the range is the quantity associated with a 95% probability (19 in 20 chances) that there is at least this amount. The high value is the quantity with a 5% probability (1 in 20 chances) that there is at least this amount. Totals for the low and high values are derived by statistical methods rather than arithmetic summation.

[d]Includes quantities considered recoverable only if technology permits their exploitation beneath Arctic ice, a condition not yet met (Source: U.S. Geological Survey, Geological Estimates of Undiscovered Recoverable Resources of Conventionally Producible Oil and Gas in the United States, A Summary, Open File Report 81-192, February 25, 1981).

the Texaco (see Reference 1-10) and Electric Power Research Institute (EPRI) reports (Reference 1-12). Figure 1-5 shows a block diagram of the overall process for producing methanol from coal. In this plant 14.5 thousand tons of coal per day is fed into the plant; output from the plant consists of 10.9 thousand tons or 13.9 million liters (or 87,309 barrels) per day of methanol in addition to sulfur and ash, which indicates an efficiency of about 75%. Efficiencies projected in a Jet Propulsion Laboratory (JPL) study (see Reference 1-10) shows efficiencies ranging from 52% to 68%.

The total plant investment is tabulated in EPRI's report (see Reference 1-12) for base year 1979, adjusted to 1981 dollars. The total capital investment requirement for plants needed to satisfy the demand projections in Table 1-3 would range from $\$5.75 \times 10^{12}$ to $\$34.8 \times 10^{12}$.

The JPL study evaluates methanol production by applying different technologies that use various feedstocks. The production cost summary under the above assumptions is shown in Figure 1-6, which indicates a production cost ranging from $0.21 to $1.34/l ($0.78 to $1.34/gal) for plants using coal, wood, or coke as feedstock and $0.16/l ($0.62/gal) for plants using remote natural gas as feedstock (all in 1981 dollars).

In another study a 120,000 barrels-per-stream-day (120,000 BPSD)[1] or 19.0-million-liter methanol plant using lignite or coal is proposed (see Reference 1-1). This plant would be located in North Dakota, where lignite

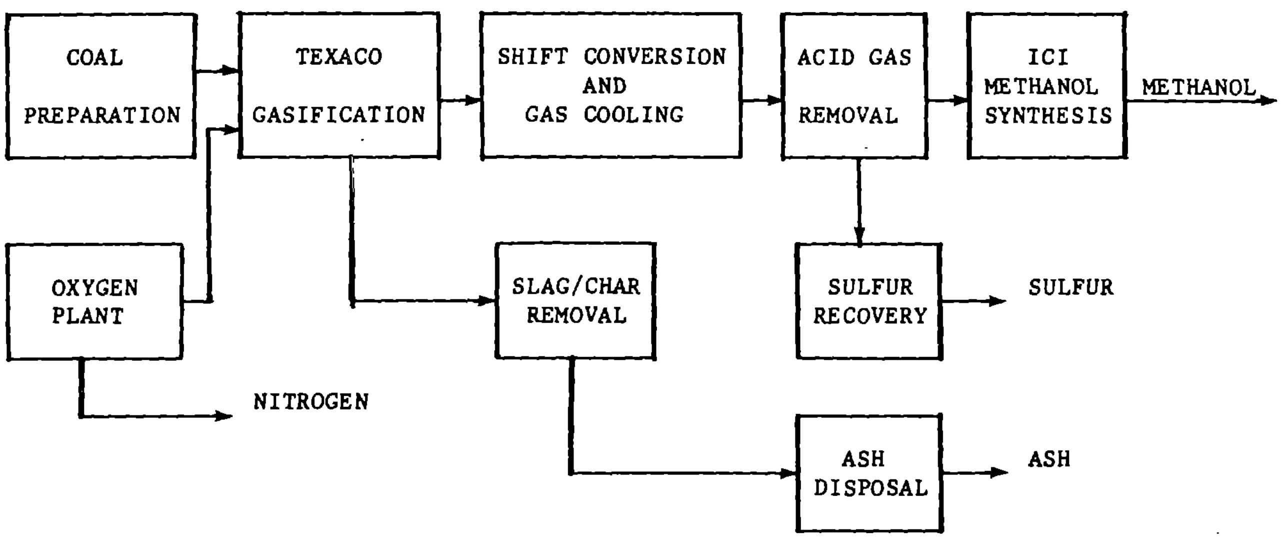

Figure 1-5. Coal-to-Methanol Plant Configuration (Source: see Reference 1-10)

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[1]Capacity per stream day and per calendar day differ by the plant operating factor, the fraction of the calendar days it is "on stream." Alcohol plants would be expected to have operating factors of about 90%.

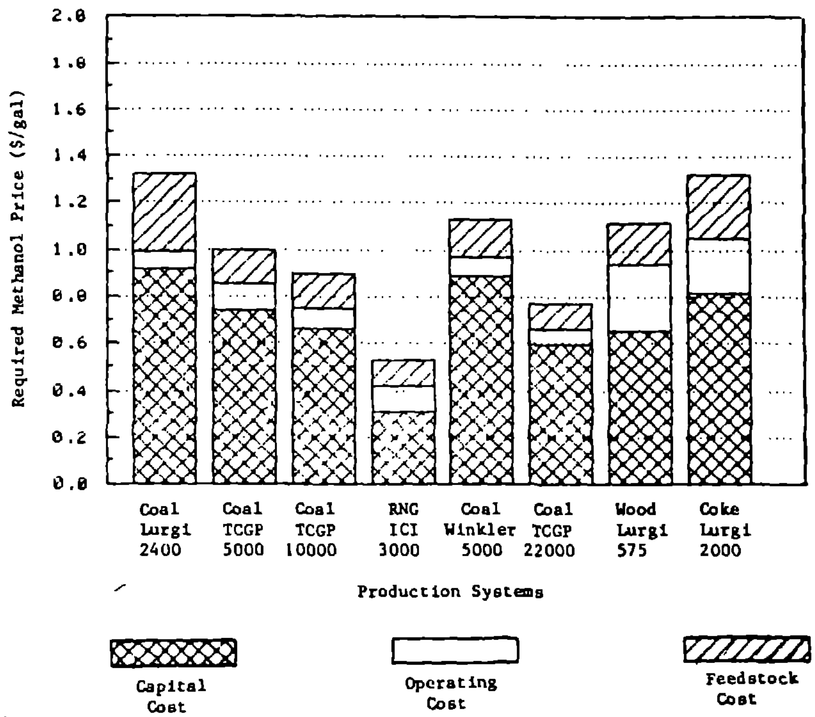

Figure 1-6. Methanol Production Cost Summary (Source: see Reference 1-10)

is abundant. The plant requires an investment of $9.40 per liter stream day ($1500 per BPSD) and an operating cost (in 1982 dollars) of $0.13 per liter ($0.49 per gallon) of methanol, based on 12% discounted cash flow, 50% tax rate, and a 13 sum-of-years, digit-depreciation method.

Production of methanol from different forms of coal (bituminous, lignite, and subbituminous) using different processes were evaluated in a report presented at the ASME Energy Sources Technology Conference (see Reference 1-5). In each case, product fuel costs were normalized to two sets of economic and financial parameters. In one case an overall annual capital charge rate (CCR) of 11.5% was used, representing utility financing; in the other uses 30% CCR represented private financing. Results of the assessment are presented in Table 1-5. Each production plant was also scaled up or down to a production of 50,000 fuel oil equivalent barrels (FOEB) per day. The capital cost for such a methanol plant ranges from $2.0 to $2.9 billion, depending on the gasifier type.

2. Natural Gas Conversion

The technology for producing methanol from natural gas is commercially proven (see Reference 1-2). Virtually all domestic methanol plants are based on natural gas, and those planned for 1982 to 1985 start-up will use natural gas as feedstock (see Reference 1-9). Potential natural gas sources include the Alaskan North Slope gas, Alaska Cook Inlet Offshore,

Table 1-5. Product Costs of Selected Coal-Liquefaction Processes (Source: See Reference 1-5)

Process	Product mix	Refined product cost, 1982$/l (1982$/gal) 11.5% CCR[a]	30% CCR
Texaco/methanol (bituminous)	100% MeOH	0.09 to 0.098 (0.35 to 0.37)	0.156 to 0.158 (0.59 to 0.60)
Koppers/methanol (bituminous)	100% MeOH[b]	0.11 (0.42)	0.18 (0.70)
Modified Winkler/ methanol (lignite)	100% MeOH[b]	0.08 (0.32)	0.15 (0.55)
Lurgi/ methanol[c]	47.9% MeOH[c]	0.09 (0.35)	0.158 (0.60)
	49.7% SNG	0.09 (0.36)	0.17 (0.63)
Lurgi/MET[c] (Subbituminous)	2.4% Gasoline	0.12 (0.45)	0.21 (0.79)

[a]In the low-cost scenario, methanol is the most economical primary product, regardless of coal type, followed by Mobil-M gasoline, H-Coal gasoline, Fisher-Tropsch gasoline, and SRC-II and EDS.

[b]MeOH-95-98% methanol, 1 to 3% water, and 1 to 3% higher alcohols.

[c]Mobil M-Gas unit capacity is only half that of total plant. Methanol and F-T unit capacity is equal to that of total plant.

Foreign Offshore, or Near Shore gas. It is estimated that 200 billion cubic meters of natural gas are flared each year because no readily accessible markets exist (see Reference 1-2).

There are several concepts advocated for plant siting, including the following: (1) location at the gas source and transporting the product by pipeline, tanker, etc., to markets, (2) location away from the gas source and transporting gas (feedstock) from source to methanol plant for processing, and (3) barge-mounted plants that can be moved to various locations to process stored gas. The first two options are promising and could utilize the existing transportation system used for natural gas. The third option is relatively independent of the site-specific variables.

Barge-mounted plants have been proposed (References 1-13 and 1-14). The concept was developed for remote locations where land-based construction and overall infrastructure are expensive or prohibitive. The advantages associated with this concept include the economy of shop fabrication and modular construction, development of remote resources that may not be economically feasible for land-based facilities, and elimination of land site. Conoco and Mitsui conducted a study for use of a floating plant for methanol production from remote gas and concluded that the concept is applicable to most off-shore or near-shore gas resources (see Reference 1-10).

The study was based on a plant producing 2.54 million liters (2,000 tons) per day of fuel-grade methanol from remote gas in southeast Asia, marketing in Japan and the United States, and transporting by 45,000 deadweight (DWT) tankers. The total plant investment was estimated to be about $450 million with operating costs estimated at about $100 to $300 million, depending upon location of the plant.

G. TRANSPORTATION OF FEEDSTOCK AND FUEL

1. Coal

Coal transport can be accomplished by rail, truck, ship, or pipeline. Historically, coal transport in this country, as well as in most nations around the world, has been accomplished primarily by railroads. Unit trains could transport coal feedstock to methanol plants located hundreds of miles away from the source of coal. A typical unit train consists of about 100 hopper cars, each with a capacity of 100 tons. For a plant requiring 14,448 tons/day of coal feedstock, two unit-train shipments per day would be required. Transport of coal by truck to methanol plants about 96 km (60 mi) or less away from the coal source may be viable, depending on the quantity of coal to be transported. The capacity of a typical truck used for conveying solid material such as coal is about 20 tons. For a methanol plant requiring 14,448 tons per day of coal feedstock, 722 truck loads per day would be required. This mode of transportation, however, is not considered a primary means of transporting large quantities of coal. Transport of coal feedstock by pipeline is by way of a slurry. Coal slurry pipelines use water as the fluid and operate traditionally on a 50% by weight mixture of coal and water for the transport of solid particles of coal.

2. Natural Gas

Natural gas is typically piped to a central point within the resource area and then transported through pipelines to the methanol plant location. Compressors are used to force the gas through the pipelines with pressures of about 900 psi. Booster stations are required every 40 to 100 mi. A study conducted in 1978 shows that about 1.6 million km (1 million mi) of buried pipeline, approximately 16.5 cm (42 in.) in diameter, could link U.S. gasfields to compressor stations and consumers (see Reference 1-9 and 1-10).

3. Methanol

Methanol can be transported by pipeline, truck, rail, and ship (tanker). About 128,000 km (80,000 mi) of pipeline were used to transport crude oil in 1977 (see Reference 1-10) and 81,000 transported finished products. Transport of methanol by truck can be accomplished by using a typical tank truck with a capacity of about 34,822 l (9200 gal). Suitable for short hauls, trucks would be appropriate for distributing methanol from a central storage location to selling centers such as gas stations but may not be appropriate for transporting finished methanol products from plant to a distribution center several hundred miles away. Rail can also be used to convey methanol in large quantities over long distances from plant to distribution center. Tankers have been used in the past for oil transport and can also be used for transport of methanol both domestically and intercontinentally. At the present time, 26,000-DWT (dead weight tons), 35,000-DWT, and 60,000-DWT tankers are used to convey the majority of coastal domestic petroleum tonnage (see Reference 1-10).

4. Transportation Costs

Unit transport cost by the various transportation modes are presented in Tables 1-6 and 1-7. It is conceivable that cost for transporting methanol would be comparable to the cost of transporting crude oil and refined petroleum.

H. FEEDSTOCK AND FUEL STORAGE

1. Coal

Storage bins can be located at the plant premises to store coal. The quantity depends on daily feedstock consumption, distance from coal source to plant location, and transportation mode used. Typically, a 15-day plant demand would be stored.

Table 1-6. United States Coal Transportation in 1977 (Source: see Reference 1-10)

Transportation mode	Percent of coal transported	Cost/ton-mile
Rail	59.1	$0.017
Truck	18.0	$0.084
Water	22.3	$0.007
Slurry pipeline	0.6	$0.017

Table 1-7. United States Crude Oil and Refined Petroleum Transportation in 1977 (Source: see Reference 1-10)

Transportation mode	Percent of crude oil transported	Percent of refined petroleum product transported	Approx (1981$) cost per 160 barrel km (100 barrel mi)
Pipeline	72.5	36.6	$0.06 ($0.09)
Truck	14.0	36.5	$0.58 ($0.92)
Water	13.2	25.1	
Tanker			$0.03 ($0.05)
Barge			
Rail	0.3	1.8	$0.34 ($0.54)

2. Natural Gas

Storage tanks can be located at the plant premises, but preferably the gas would be piped from the resource base into the production plant. A 15-day plant demand would be stored.

3. Methanol Storage

Location, capacity, and safety of storage tanks are among factors to consider for storage of a methanol product. Storage tanks are located at the point of use, i.e., gas stations. One assessment suggests that fiberglass tanks in sizes up to 75,700 l (20,000 gal) are suitable for low viscosity fuels such as methanol, which requires no heating (see Reference 1-10). Other small underground tanks fabricated with mild steel could also be used.

I. METHANOL PRICES

1. Historical Prices

Domestic wholesale prices of methanol have increased from $0.07/l ($0.27/gal) in 1965 to $0.20/l ($0.75/gal) in 1981. These prices as well as producer prices are shown in Table 1-8 (Reference 1-15), representing an average annual rate of change of 6.6%. The price for the first quarter of 1982 ranged from $0.19 to $0.20/l ($0.70 to $0.75/gal). Methanol plants in operation use natural gas as feedstock; some plants designated for operation beyond 1990 are designed to use coal as feedstock.

Table 1-8. Historical Methanol Prices (Source: see References 1-11 and 1-15)

Year	Price,[a] ¢/l	Price,[a] (¢/gal)	Producer Price,[b] ¢/l	Producer Price,[b] (¢/gal)
1965	7.0	(27)	5.5	(21)
1967	6.9	(26.7)		
1968	6.6	(25)		
1969	6.6	(25.4)		
1970	6.9	(26.7)	2.9	(11)
1971	6.0	(22.8)		
1972	2.8	(10.7)		
1973	3.5	(13.5)		
1974	5.5	(20.9)		
1975	10.3	(39)	10.6	(40)
1976	10.3	(39)		
1977	10.3	(39)		
1978	11.4	(43.1)	9.2 to 10	(35 to 38)
1979	11.6	(44)	12.2	(46)
1980	16.4	(62)	13.2 to 16.9	(50 to 64)
1981	19.8	(75)	18.5 to 19.8	(70 to 75)
1982[c]	18.5 to 19.8	(70 to 75)		

[a]Wholesale price.

[b]The producer price is the realized market price as opposed to the list price, which is often considerably above the market price.

[c]First quarter.

2. Projected Prices

Assume that coal will be the dominant feedstock for these plants in the 1990s; price estimates can then be made from plants using, or projected to use, coal as feedstock. The production cost of methanol from coal was estimated to range from \$0.08 to \$0.21/l (\$0.32 to \$0.80/gal) in 1982 dollars. An EPRI Study (see Reference 1-12), based on a 33,860 FOEB-per-day methanol plant, concluded that, for a non-regulated producer with 100% common-equity capital, the price of methanol is \$0.13/l (\$0.49/gal); that of a regulated utility producer with 50% debt capital and 12.25% per year interest on debt would be priced at $0.08/l ($0.32/gal).

Hagler, Bailly, & Company presented results of a study (see Reference 1-15) that estimated the minimum acceptable price (MAP)[2] of methanol from an analysis of methanol plants under seven economic, financial, and/or performance assumptions. The results indicated nominal prices of $0.40 to 0.58/l ($1.50 to 2.20/gal) for 1995. In the same study, a 96% gasoline/4% methanol blend (by volume) and a 92% gasoline/8% methanol blend were analyzed. The results indicated a price of $0.53/l ($2/gal) for heat fuel, $1.1/l ($4.25/gal) for 8% blend, and $1.59/liter ($6.00/gal) for 4% blend in 1995.

Wagner's study (see Reference 1-1) analyzed a 120,000-BPSD[3] methanol plant located in North Dakota that used liquite as feedstock, resulting in a methanol price of $0.13/l ($0.49/gal) in 1982 dollars.

Required factory-door prices for methanol produced from various feedstocks were estimated from a number of studies and adjusted to a common basis (Reference 1-16). The results of the study are shown in Figure 1-7. Using an average contract cost of $1.30 per mm Btu, the price of methanol was estimated to be $0.19/l ($0.72/gal) in 1980$ or $0.22/l ($0.84/gal) in 1982 dollars when adjusted with the Data Resources, Inc., Gross National Product (DRI GNP) deflator (Reference 1-17).

The California Methanol Assessment indicated retail prices of methanol at the pump (Table 1-9). As previously mentioned, a 79,800-l/day (22,000-gal/day) methanol output plant using western coal as feedstock with TPO/ICI technology was selected as the candidate plant for this analysis. Table 3-20 in that study indicates a retail price in 1995 of approximately $0.34/l ($1.30/gal) in 1982 dollars, which translates to $0.375/l ($1.42/gal), using the DRI GNP deflator. This estimate is reasonable, considering the present retail price of $0.24/l ($0.90/gal) at the pump.

J. INTRODUCTION OF METHANOL INTO FUEL MARKET

The United States has observed the introduction of new fuels such as unleaded gasoline and alcohol blends into the fuel market during the past decade. The experience gained from this exercise is applicable to methanol. As methanol-fueled cars emerge in the market, stations selling methanol fuel are expected concurrently to become available.

One alternative automotive fuels report (see Reference 1-4) indicates that alternate-fuels market penetration will occur in four phases. Phase 1

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[2]MAP includes cost of production, cost of servicing debt, and cost of rewarding the plant owners for the equity invested in the project.

[3]Barrels per stream day.

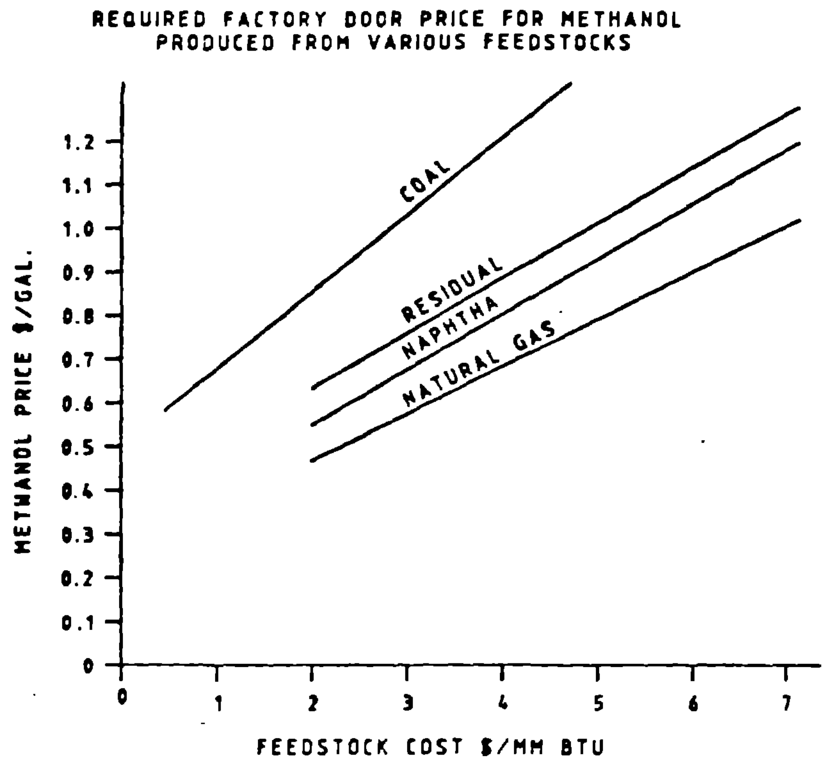

Figure 1-7. Required Factory Door Price for Methanol Produced from Various Feedstocks (Source: see Reference 1-16)

Table 1-9. Retail Prices at the Pump[a] (Source: see Reference 1-10)

Year	Remote natural gas		5,000 tons/day Western coal		10,000 tons/day Western coal	
	Plant Gate	Retail	Plant Gate	Retail	Plant Gate	Retail
1982	NA	23.8(90.0)	NA	NA	NA	NA
1987	16.1(61.0)	21.6(81.7)	25.4(96.0)	34.2(129.5)	NA	NA
1992	16.6(63.0)	22.4(84.6)	26.4(35.5)	23.5(134.5)	23.5(89.0)	33.1(125.4)
1997	17.2(65.0)	23.2(87.8)	NA	NA	24.8(94.0)	34.8(131.8)

[a]In ¢/liter (¢/gallon).

will occur during the 1980 to 1990 period when the transportation fuels market will be dominated by petroleum fuel with insignificant amounts of alternate fuels. The next period (1990 to 2010) is projected to be dominated by fuels from petroleum with modest but increasing contributions of alternate fuels. The third phase shows comparable amounts of fuels from petroleum and alternate fuels within the 2010 to 2030 time period. The report theorizes that alternate fuels will dominate the transportation fuels market beyond 2030. Figure 1-8 shows the projected changes in fuels and engines during this period.

Suggestions that have been offered for methanol fuel introduction include captive fleets, methanol/gasoline blends, multi-blend fuel pumps, and regional introduction (see Reference 1-5). While introducing methanol by captive fleets has the advantage that experience could be gained by both vehicle and full developers concerning vehicles and fuel, it has the disadvantage that the general public would not also gain experience. Introducing methanol/gasoline blends is compatible with existing fuel-distribution systems and vehicle fleets. The case of multi-blend systems has the advantage that neat (non-blended) methanol as well as other blends are already available at the pump.

K. SUMMARY OF METHANOL AVAILABILITY

There are sufficient coal resources after meeting other demands to serve as feedstock for large-scale production of methanol. Conversion technology is

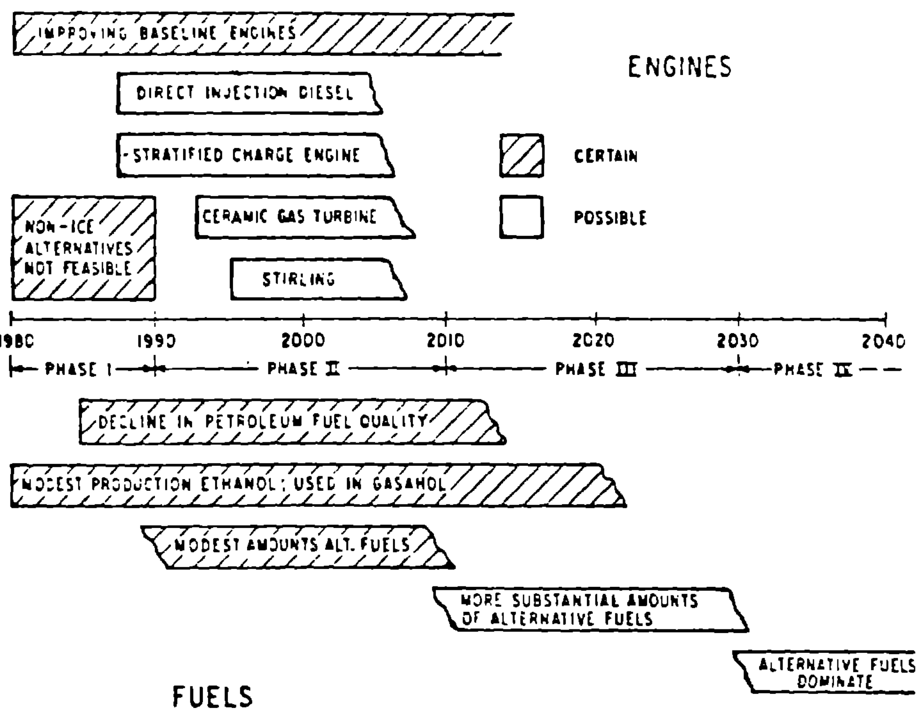

Figure 1-8. Possible Engines/Fuels Transition
(see Reference 1-4)

commercially proven for production of methanol from coal. Existing transportation networks for both feedstock and product could be modified and expanded to support a large-scale methanol industry. However, planned production is insufficient to meet the transportation demand in the event of petroleum scarcity during the next decade or two. Hence, AVs using liquid fuels (i.e., advanced conventional vehicles, hybrids, and fuel-cell vehicles) should be designed to save fuel.

The present price of $0.24/l ($0.90/gal) is expected to rise to $0.37/l ($1.42/gal) in 1982 dollars by 1995. Current total domestic production is 4.77 billion liters (1.26 billion gallons) from natural gas, but it is expected to double by 1990. To meet the demands of a methanol-based fleet the production level must increase 10 to 40 times in the next decade, depending on the vehicle-mix scenario, which would have a substantial effect on the price scenario.

SECTION II

ELECTRICITY AVAILABILITY

A. INTRODUCTION

The introduction of advanced vehicles on a large scale into the transportation system will mean an additional load for the utilities and require specific service and refueling facilities. This section addresses the capability of the utility industry to respond to the requirements for servicing electric vehicles EVs, including rapid recharging.

The additional load imposed on the utilities as a result of the introduction of the AV represents a new type of demand on utilities: an appliance load to be satisfied when and as it is demanded. It has its own magnitude, duration, and shape characteristics and will be superimposed on the existing utility-load curve with results that can affect the technical and economic viability of AVs. The technical considerations include harmonic sources from battery chargers and their potential effect on the utility grid as well as the transmission and distribution system. The economic viability is viewed from the standpoint of the utility as well as the AV consumer.

From the utility viewpoint, the economic viability is in terms of potential for load leveling and, therefore, potential reduction of the average cost of generation. The consumer views the viability in terms of (1) potential electricity price reduction, resulting from the utility generation cost reduction that may be passed on to the consumer and (2) the convenience in servicing and refueling AVs. For example, a vehicle owner may find it desirable to refuel within the time normally spent to refuel conventional vehicles, i.e., 10 to 20 min. Moreover, he will need to refuel when and where needed. Therefore, rapid recharge, availability of service, refuel facilities, and the utilities' electricity production capability are among important requirements for supporting an AV market. In the following section, electricity supply prospects are discussed.

B. ELECTRICITY SUPPLY

The projections of future electricity supply are based on the examination of potential AV consumer demands. In the near term, potential electricity supply includes generation from coal, oil, nuclear, and other sources. In the long term, beyond 1990, it is anticipated that electricity generation will move away from petroleum.

Future shortages of electricity may be due to shortages in generating capacity, transmission, fuel supply, or any combination of these. Capacity shortages could arise if there is insufficient installed capacity or if plans to install adequate capacity are delayed. Generating capacity could be constrained by transmission. It is anticipated that there will be enough generation capacity to supply the electricity needs during the 1990s. Excess generating capacity exists now as a result of peak-load forecasts made in previous years. This situation makes it possible to supply electricity with facilities already installed; therefore, production costs could be relatively low. Reserve generation capacity will be maintained, but it is expected to decline slightly.

Shortages of electricity due to inadequate transmission have been reduced significantly through the coordinated efforts of the North American Electric Reliability Council. This body, working through the individual reliability councils, coordinates the activities of neighboring utilities involved in the transmission system, so that help is provided where needed when there is inadequate transmission.

Electric utilities have embarked on a program to alleviate the problem of fuel shortages by planning for the addition of coal units (Reference 2-1) and converting existing oil-burning units to use other fuels.

C. ABILITY OF UTILITIES TO MEET ADVANCED VEHICLE LOADS

Various studies have been made during the past few years to evaluate the ability of utilities to supply electricity for electric vehicle recharging. An EPRI study (Reference 2-2) presents a typical daily power level projection for all utilities in the United States for the year 2000 (Figure 2-1). It is evident from the figure that the load is substantially lower at night, and recharging of AVs could possibly occur between 11:00 p.m. and 6:00 a.m. without requiring additional generation capacity, depending on the size and distribution of the load.

The same study assumes that electric vehicles would be recharged overnight and took the following approach. Data was used from the 1977 Nationwide Personal Transportation Study (NPTS) to determine travel distances and the distribution of times when personal vehicles finally return home. Information on distributions of final parking times and distances traveled by commercial vehicles were not available in that database, so commercial vehicles were not included in the study. The resulting distribution is shown in Figure 2-2.

Figure 2-2 indicates that most personal vehicles arrive at home between 4:00 and 6:00 p.m. This information was used with an assumed recharging profile and assumed vehicle performance data to determine the required power needed for recharging. This was used as an input to the General Research Corporation (GRC)/DOE Recharge Capacity Projection (RECAP)[4] model, which estimates power demand and fuel types required by individual utilities to satisfy demand.

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[4]RECAP is a model originally constructed by GRC for DOE. It projects hourly loads and generation for nearly 300 individual utilities in the United States. Its projections of future demand come from utility reports to DOE and reliability council forecasts.

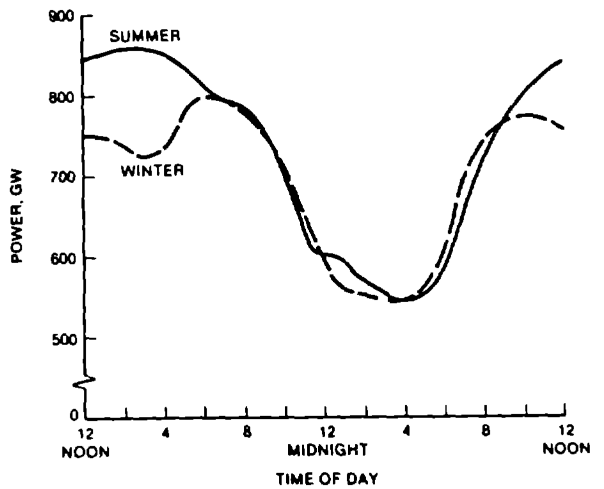

Figure 2-1. Projected Daily Load Curve in the Year 2000 (Source: see Reference 2-2)

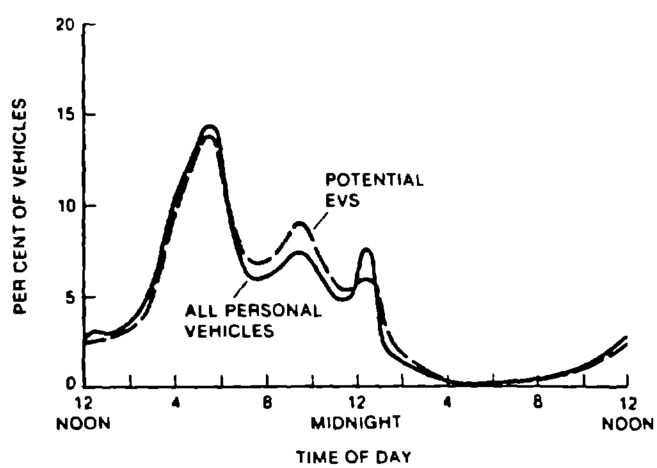

Figure 2-2. Distribution of Times of Final Return Home (Source: see Reference 2-2)

D. RECHARGE TIME AND LOAD

Three recharge times were investigated (Figure 2-3). The earliest possible recharging could occur when the vehicle returns home. The latest possible recharging could occur at a point in time so that the needed full charge could be accomplished before the vehicle is required for use in the morning. The third time was a nominal 6:00 a.m. finish.

The number of AVs in the market must be assumed to assess the impact. Projections of electric-vehicle market penetration vary widely, and Figure 2-4 shows several projections. GRC projected 1% of the personal vehicles in 1990 and 5% (7.5 million) in the year 2000 would be electric vehicles (Reference 2-3). In studies to determine the impact of electric vehicle, DOE projects 24 million electric vehicles EVs by the year 2000 (high scenario) and assumes that 20 million of these will be driven and recharged on a given day (Reference 2-2).

Figure 2-5 shows the impact of different recharge times on daily power levels. It is evident from this graph that charging 20 million electric vehicles or then return home could add to the peak; charging with a 6:00 a.m. finish is more desirable.

EPRI and GRC assumed a 5% (7.5 million) electric vehicle penetration in the year 2000 for input into the RECAP model. The result is shown in Table 2-1. It is clear that oil use nationwide for recharging vehicles at the earliest possible start is almost twice that for recharging that has been delayed to finish at 6:00 a.m. It should be noted that the fuel sources are non-uniform throughout the nation; consult Reference 2-2 for details.

An Argonne National Laboratory study (Reference 2-4) considered electric vehicles of 80- to 240-km (50- to 150-mi) range and analyzed the impacts under five electric-vehicle market penetration scenarios. Recharging loads for

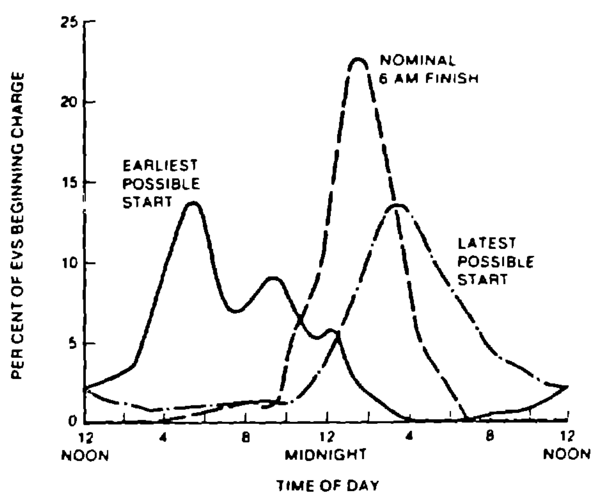

Figure 2-3. Distributions of Times for Beginning Overnight Recharging (Source: see Reference 2-2)

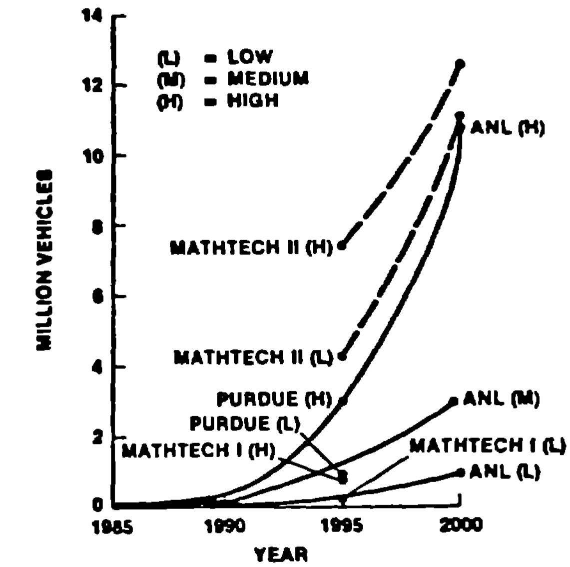

Figure 2-4. Projections of Electric Hybrid Vehicle Market Penetration (Source: see Reference 2-2)

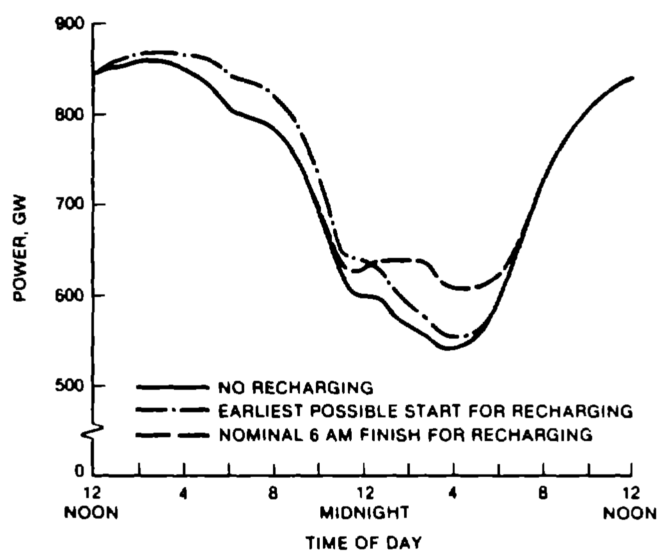

Figure 2-5. Effect of Overnight Charging of 20 million Electric Vehicles in the Year 2000 (Source: see Reference 2-2)

Table 2-1. Energy Use to Recharge Electric Vehicles Nationwide[a] (Source: see Reference 2-2)

Recharging policy	Total 10^6 GWh	Fuel type, %				
		Nuclear	Coal	Oil/Gas	Other	Unknown
Finish at 6:00 a.m.	50.5	3.9	73.7	16.1	5.1	3.6
Earliest possible start	50.5	1.1	59.9	27.1	7.5	4.2

[a]Overnight recharging in the year 2000; EV penetration 5% (7.5 million).

vehicles were determined for each of the 158 Urbanized Areas (UAs) in the United States. This was input into the RECAP model with results showing electricity demand and fuel types needed by each UA to meet the demand. Data were aggregated for the 10 federal regions and national totals.

The ANL study concluded that the impact of electric vehicles on electric utilities is small from the present time to the year 2000. However, for selected areas such as New York and New Jersey the electricity demand represented a sizable fraction of electricity demand in the year 2000 and needed to be included in utility planning.

In summary, the studies showed that the utilities could support from 20 to 60 million electric vehicles, depending on the regional acceptance and the level of charger control to conform to the available energy.

Estimates were made for the number of AVs that the utilities could support, based on vehicle data from the AV assessment and EPRI's projections of energy availability. Energy consumption of the AVs varied from 125 Wh/km (200 Wh/mi) to 187 Wh/km (300 Wh/mi). Assuming an average value of 156 Wh/km (250 Wh/mi) and an average of 16,000 km (10,000 miles) per year, the annual energy requirement would be 2500 kWh per vehicle. If 25 to 50% of the available off-peak energy could go for AV recharging, 30 to 70 million electric vehicles could be supported with the presently available off-peak energy (assuming optimum charger control).

Rapid recharging electric vehicles would complicate and possibly negate the effects of the utility efforts to load-level their current facilities. Because this power is required on demand, new capacity would be required to meet the recharging needs that would occur at peak periods. For example, a typical AV that uses 150 Wh/km would require 60 kWh to be replaced in a relatively short time at the service station after a 400-km trip. This could require 200 to 400 kW to refuel in 15 to 30 min, which is clearly unacceptable from the supply standpoint. Also, most of the batteries considered in this analysis would not accept a full charge in less than about an hour.

E. ELECTRICITY PRICES

The average price of electricity in the United States increased by 17.6% in 1981. All regions experienced increases greater than inflation, except the northwest, which relies heavily on hydroelectric power. The Pacific Coast had an average price increase of 26%, being heavily dependent on oil, gas, and purchased power. Electricity prices varied substantially around the country in 1982, from less than 1¢/kWh in the northwest to almost 20¢/kWh in the northeast (7¢/kWh median in February 1982).

Future prices of electricity will depend on production costs and rates established by the various regulatory bodies. It is reported that more than 75% of electric generating capacity needed for 1991 is already installed and at costs that were a fraction of current cost (see Reference 2-1). This means that production costs are likely to be relatively lower.

Data Resources, Inc. forecasted average residential electricity prices to increase to 31¢/kWh in the year 2000 (see Reference 1-17). This is an average annual rate of change of 9.3%. Coal's share of electricity production is expected to be slightly more than 60% by the year 2000, according to DRI's forecast. This forecast, adjusted to 1982 dollars, is presented in Table 2-2.

Pricing electricity by Time-of-Use (TOU) or Time-of-Day (TOD) is not in common use in the United States. Experiments are currently being conducted at various utilities (Detroit Edison and Southern California Edison) to study its engineering and economic viability. If significant quantities of AVs penetrate the market, it may be desirable to introduce such a pricing scheme to help load management. Time-of-use electricity price depends on the season of the year and the time of day the electricity is consumed. Fifty percent of the national average electricity price (5¢/kWh) was assumed for the AV economic analyses.

F. IMPACTS OF ADVANCED VEHICLES ON TRANSMISSION AND DISTRIBUTION

EPRI has assessed the impact of electric vehicles on utility systems (References 2-5 and 2-6). Utility power production, transmission, and distribution systems are based on an alternating current and voltage that are sinusoidal in nature. When electric loads consisting of inductances, capacitances, and resistances in any combination are connected to this utility system, the sine wave is preserved; and the system components are said to be linear. When nonlinear devices such as battery chargers are connected to the utility system, the fundamental sinusoidal shape of their current flowing through the system is changed. However, it should be noted that electric battery chargers like the one used in the Rippel electric car (Reference 2-7) uses a modulation technique that results in an in-phase sinusoidal current drain.

Harmonic currents that otherwise develop cause a voltage drop across the inner impedance of the power-supply system. This voltage drop imposes a non-perfect sine wave voltage at the user's point of connection. The harmonic voltage drops are superimposed over the electrical distribution system. Even if those harmonic voltages are relatively small compared with the system's

Table 2-2. Average Residential Electricity Price (in 1982¢/kWh)[a]

Region	Year 1990	Year 1995	Year 2000
New England	9.08	10.15	10.40
Mid Atlantic	8.33	8.71	9.20
South Atlantic	7.36	9.47	10.08
E. North Central	7.87	8.49	8.90
W. North Central	6.95	7.54	8.05
E. South Central	6.86	8.36	9.27
W. South Central	9.37	11.04	12.37
Mountain #1	8.29	8.24	8.55
Mountain #2	9.79	9.54	10.70
Pacific #1	4.03	4.86	6.63
Pacific #2	8.27	11.51	12.19
Average U.S.	7.80	9.72	9.90

[a]Source: Adjusted from Data Resources, Inc., Energy Review, Reference 1-17.

fundamental voltage, orderly system operation may be disturbed if the harmonic voltages exceed a certain level.

With the introduction of advanced vehicles using batteries and battery chargers, the number of devices that produce harmonics will grow. Harmonic levels on the utility distribution system will also continue to rise and consequently affect the system output and economics. Yet, it should be made clear that technology already exists that produces low levels of harmonics (approximately 1% distortion).

G. REFUELING AND SERVICE FACILITIES

The consumer considers the electric vehicle market from the standpoint of convenient refueling and service facilities as well economics. Possible service systems for recharging EV batteries include home refueling, distributed refueling at locations such as parking lots, shopping centers, roadside stations, restaurants and theatres, as well as service facility refueling at service stations.

1. Home Refueling

Home refueling is convenient but could be complicated by the use of non-conventional batteries such as the zinc-chlorine, which requires a refrigeration system. Vehicle batteries that outgas substantially are a safety concern for the consumer.

2. Distributed Refueling

Lawrence Livermore National Laboratory conducted a study (Reference 2-8) to determine the number of electrical outlets needed for distributed refueling. Distributed refueling facilities included a variety of locations, such as airports, amusement parks, restaurants, and night clubs. Recharge times assumed were 15 and 30 min, 1 and 2 and 8 h. The determination was based on an analysis of the driving habits of the average motorist. Assuming 30 million EVs in the country and 29% of the miles traveled by these vehicles using distributed recharge for refueling purposes, LLNL concluded that over 1.6 million outlets would be necessary to supply recharge service. This would imply over 1 million outlets for the 20 million EVs estimated by the DOE in 1990.

3. Service Facility Refueling

Service station refueling could require two types of service: battery-exchange facilities and battery-charging facilities. Battery-exchange facilities would require battery-exchange areas, a battery-service area for cleaning and repairing batteries, and a battery-storage area for storing and charging batteries. Assuming driving patterns and trip statistics compiled by the U.S. Federal Highway Administration and making the assumption that 25% of already existing 150,000 service stations are retrofitted to accommodate battery exchange, the Lawrence Livermore study showed that the number of exchanges per station would be over 25,000 per year. Vacation travel accounts for 2.5% of all travel and averages 256 km (160 mi) one way; 7.5 billion battery exchanges would be required. The transportation of this quantity of batteries and the uncertain condition of the batteries upon exchange are major deterrents to this scheme. The use of more than a few types of batteries would make battery exchange nearly impossible because many batteries have unique maintenance requirements.

H. CONCLUSION

Utilities have the capability to support an AV market of reasonable size without significantly affecting their generation and transmission if electric vehicles are charged with excess energy off-peak. Rapid recharge is not feasible due to the large power requirement. Battery exchange would be an extremely difficult logical problem and would test the faith of the consumer with regard to the quality of the replacement battery.

The national average electricity rate is expected to be 10¢/kWh (1982$) in 1995 although regional costs will vary from 30% to 200% of this value. The time-of-day rate is expected to be 5¢/kWh in the time reference of interest.

SECTION III

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