REFERENCE

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RESEARCH AND DEVELOPMENT OPPORTUNITIES FOR IMPROVED TRANSPORTATION ENERGY USAGE

Summary Technical Report of the Transportation
Energy R&D Goals Panel

DEPARTMENT OF TRANSPORTATION • UNITED STATES OF AMERICA

SEPTEMBER 1972

This report reflects the views of the Transportation Energy Panel which is responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policy of the Federal agencies participating on TEP. The report does not constitute a standard, specification, or regulation.

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16. Abstract The almost complete dependence of transportation systems upon petroleum products makes the transportation sector vulnerable to increased prices of petroleum or insecure sources of petroleum. Since the dependence of transportation upon imported petroleum is projected to increase substantially over the next two decades, both short-and long-term remedial actions should be initiated now and in the next few years because of the long time needed to bring about evolutionary changes in the Nation's transportation systems. Possible remedial actions include:

1. Technological improvements for more efficient use of petroleum by transportation.
2. Technological changes to permit greater use of non-petroleum energy resources by transportation.
3. Shift of transportation demand to more efficient modes from less efficient modes.
4. Reduction of demand for transportation services.

Transportation energy demand projections are given and R&D tasks in each of the first three categories are assessed.

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PREFACE

This document is the final report of the Transportation Energy Panel (TEP) prepared for the Office of Science and Technology (OST). It is submitted to the OST-sponsored Energy R&D Goals Committee for consideration as part of the 1972 Energy R&D Goals Study. The TEP is an interagency ad hoc Panel, sponsored by the Office of the Secretary, Department of Transportation (DOT), with participation from the Department of Defense (DOD), the Environmental Protection Agency (EPA), the Office of Science and Technology, and the National Aeronautics and Space Administration (NASA).

The report documents the TEP assessment of relevant technology for improving the usage of national energy resources by the transportation sector. Technologies for improving energy extraction, conversion, transmission and usage by other economic sectors, are dealt with by other panels participating in the 1972 Energy R&D Goals Study.

In pursuit of its study, TEP sponsored several workshops, briefings, and coordination meetings which had personnel from a variety of Federal, academic, and industrial organizations. All are gratefully acknowledged in Section VII of this report. Emphasis was given both to transportation demands and to relevant technology assessment. During these meetings, the participants were invited to make presentations to the Panel, submit documents, and answer questions, as appropriate. The information received was assessed and organized by TEP subpanels, and this is included, in part, in the Technical Appendices to this report. Overall assessment and recommendations by TEP are delineated in this Summary Technical Report.

The names of the TEP members and their affiliations are given below.

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TECHNICAL APPENDICES

I. INTRODUCTION AND BACKGROUND

The work of the Transportation Energy Panel (TEP) started with consideration of the following factors affecting the requirements for more efficient and more diversified utilization of transportation energy:

1. Transportation consumes about 25% of our domestic energy and is expected to continue at the same rate in the foreseeable future.

2. Transportation is a major user of petroleum. Fifty five percent of the petroleum consumed in the USA is used by transportation. This fraction is projected to increase to 60% in the mid-eighties.

3. Transportation is intensively dependent on petroleum--more than 98% of the transportation energy consumed is from a petroleum-based energy source.

4. Assuming no major changes in Government energy policy U.S. oil imports are projected to reach 50% of the total domestic oil consumption in the mid-1980's. Moreover, future acquisition of foreign oil may be subject to instabilities.
5. Finally, it is recognized that resources other than domestic or imported oil, such as shale oil, coal, and nuclear energy might be plentiful but an adequate yearly production to meet transportation needs may be difficult or costly to obtain.

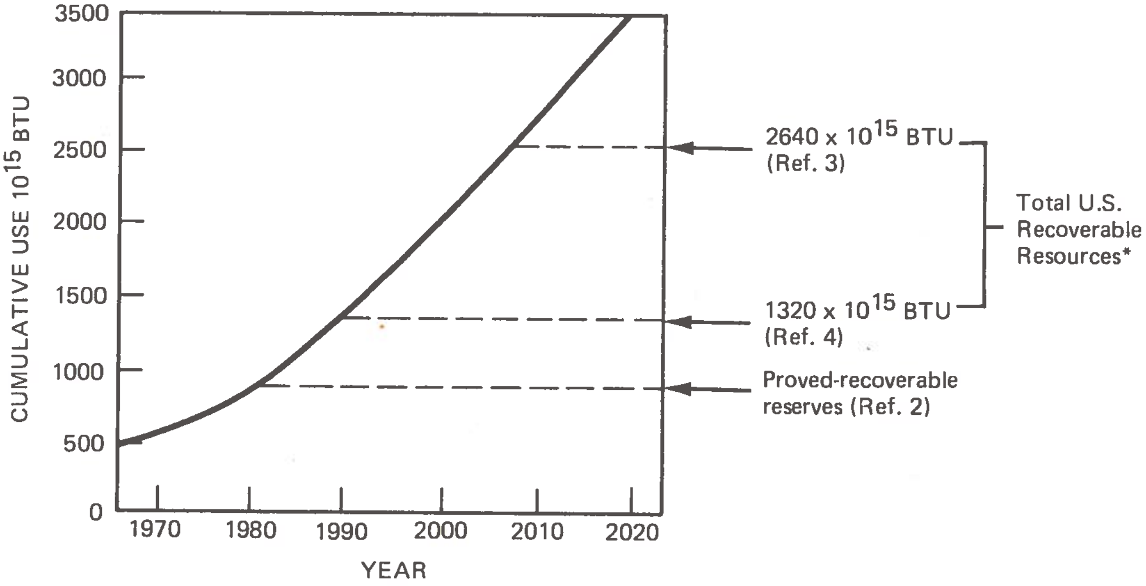
The demand and supply situation is summarized in Figures I-1 and I-2. Figure I-1 presents the projected cumulative U.S. demand for oil in the period 1970 to 2020 as extrapolated from present trends without any adjustment for greater efficiency of utilization of transportation and fuel. A comparison is made with several levels of reserve and resource estimates, appropriately referenced. The projected production and consumption picture is illustrated in Figure I-2.

In view of the aforementioned projections, the TEP found the following reasons for Federal concern:

1. The short term effect of transportation emission controls will increase automotive fuel consumption by 20% to 25%.

2. The automobile industry and manufacturers have had little incentive to use effective fuel economy measures, or to consider fuel diversification.

3. Policymakers require well-founded information about practical fuel economy measures, and possible fuel diversification.



*INCLUDES "UNDISCOVERED RECOVERABLE" AND "PARA-MARGINAL." INCLUDES ALASKAN DEPOSITS AND ALL NATURAL GAS LIQUIDS.

Figure I-1 - Cumulative Petroleum Demand Versus Domestic Supply Estimates

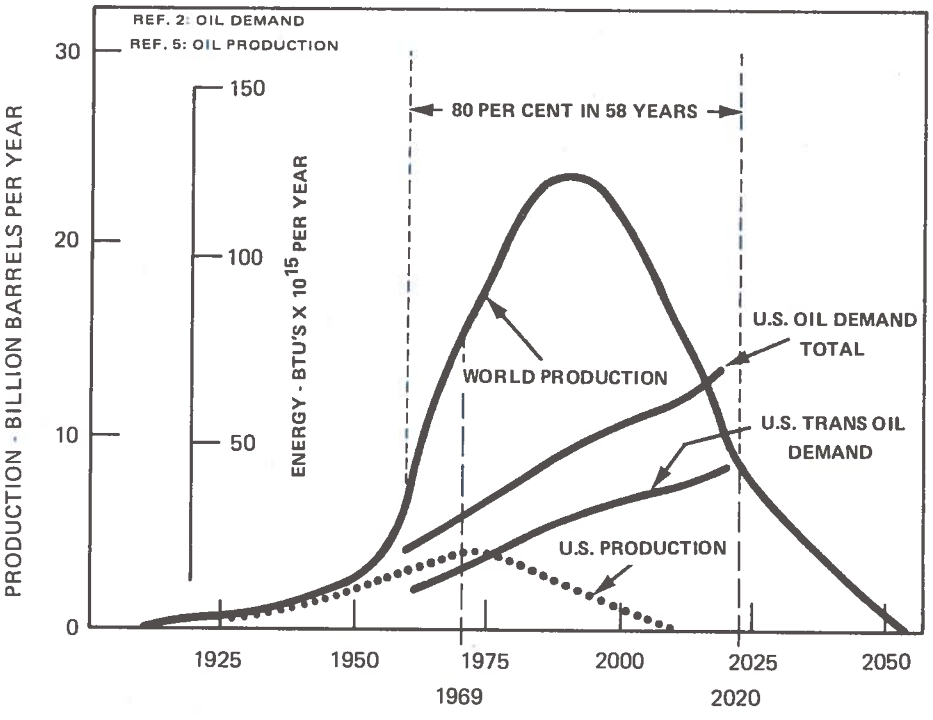


Figure I-2 - Oil Market

4. Finally, long-range solutions require certain new technologies and the exploration of technological options in conventional and unconventional propulsion and vehicle systems.

The Panel directed most of its efforts toward the assessment of technology-oriented options. It is realized that options other than technological exist, however. For orientation purposes, consider the matrix in Table I-1. It is not an all-exclusive matrix of options, but it is useful for illustrative purposes. The entries in the left column are arranged in order of increasing generality, the most specific item being the propulsion subsystem, and the most general item being the Transportation Modal System. The three entries on the top row correspond to the means of impacting energy consumption.

Again the entries made in the different squares of this matrix are for illustration only. There is no assertion that each entry has a beneficial impact on energy consumption. Most entries are self-explanatory except for the acronym TOPICS, which stands for Traffic Operations for Improved Capacity and Safety, a program sponsored by the Federal Highway Administration.

Examining this matrix, TEP realized two things: first, other entries can be made, and second, the assessment and evaluation of most entries is a complicated matter. Entries may be interrelated and the final result may not be favorable to transportation energy consumption, or even to total energy consumption. TEP has given some attention to the potential value of entries in squares no. (7) through (12), however, detailed and well-considered assessments could not be made in view of the time and resources available to the Panel. Moreover, these subjects are continually receiving R&D attention by transportation-oriented interests, as opposed to energy-oriented R&D *per se*. In summary, TEP has emphasized the assessment of the technology-oriented subjects appearing in entries no. (2), (3), and (5), leading to more efficient and fuel-diversive transportation, both for the currently implemented systems as well as technology for systems projected in the future.

In these areas, the Panel found that technological improvements and changes have the potential to significantly reduce the projected energy demand of the Nation's transportation system on petroleum within the next 15 years, and to permit the use of non-petroleum-based energy sources by the end of the century.

For organizational purposes, the Panel divided the assessment of transportation technologies with lower power consumption from those with higher power consumption. Lower power vehicles are mainly autos and trucks. They are generally operated and serviced on an individual basis. The

TABLE I-1 POSSIBLE STRATEGIES FOR IMPACT ON TRANSPORTATION ENERGY

Remedial Action / System	Reduce Demand	Improve Efficiency	Diversify (Substitute)
Propulsion Subsystem	(1) Power Limits	(2) Improved Engines Improved Load Match to Prime Mover	(3) New Engines New Fuels Electric-Propulsion
Vehicle	(4) Smaller Vehicles Lighter Vehicles	(5) Reduce Rolling Resistance Reduce Aero-Drag Reduce Other Losses	(6) New Vehicles
Guideway	(7) Roadway Design	(8) TOPICS Traffic Controls	(9) People Movers Dedicated - Guideways
Transportation Modal System	(10) Staggered Work Hours Proper Land Use 4-Day Week New or Modified Regulations	(11) Modal Shifts	(12) Telecommunications

vehicles at higher powers are mainly aircraft, vessels and rail. They are usually operated and serviced in fleets and are more strictly regulated.

Opportunities at Lower Power

The technological opportunities at lower powers were reviewed and assessed in three distinct groups as follows:

1. Technology for Fuel Economy

2. Improved Engines and Fuel Diversification

3. Electric Propulsion Technology

Technology in the first group is virtually available now, and only optimization and demonstrations are needed before implementation. Moreover, implementation could start a few years from now and it would produce a relatively minimum deviation from the status quo. In the second group, the report reviews and assesses the potential of new engines for better fuel economy and novel fuel compatibility with respect to the present engine alternatives. Such engines could become available for implementation anytime between 5 and 15 years from now and, depending on the engine, could produce moderate deviation from the status quo.

The technology of electric propulsion was reviewed and assessed separately. Both wayside electric and battery electric propulsion systems were considered. Wayside electric propulsion for the large scale road network in the country is deemed economically unattractive, whereas it is and will be both economical and needed for many heavily-traveled urban routes. Battery technology is currently inadequate for use in full performance automobiles. Many years (say 15 to 20 years) of R&D are estimated as necessary before electric propulsion could reach the stage of large scale implementation. A large scale implementation of this technology would produce a major deviation from the status quo.

The above time scales refer to readiness for implementation. An additional 10 years is required for full automotive implementation (replacement of existing population). Thus, the benefits of fuel economy technology could be realized gradually, but not fully, before 1985. Similarly, for new engines and new fuels, the full realization of benefits could not be reached before 1990 to 2000.

Finally, an all-electric ground transportation could be realized by the end of the century, provided that R&D is successful.

Opportunities at High Power

The technology opportunities at high power have been reviewed and assessed in three areas: Air, Marine, and Rail Transport. Near term impact on fuel consumption of these modes is more difficult than for the automobiles because of longer life and higher support investment of the vehicle inventories. Major modal alternatives exist in the intermediate and long term which deserve continued study and economic impact assessment. Some of these have been considered to alert the Energy R&D Goals Committee about future opportunities now envisioned. It is noted that the potential expenditures for advanced development in these areas are substantial. Since the benefit is yet to be determined from a national transportation viewpoint, TEP limits its recommendations to continued study and exploratory technology development.

II. EXECUTIVE SUMMARY

Abstract

The almost complete dependence of transportation systems upon petroleum products makes the transportation sector vulnerable to increased prices of petroleum or insecure sources of petroleum. Since the dependence of transportation upon imported petroleum is projected to increase substantially over the next two decades, both short- and long-term remedial actions should be initiated now and in the next few years because of the long time needed to bring about evolutionary changes in the Nation's transportation systems. Possible remedial actions include:

1. Technological improvements for more efficient use of petroleum by transportation.

2. Technological changes to permit greater use of non-petroleum energy resources by transportation.

3. Shift of transportation demand to more efficient modes from less efficient modes.

4. Reduction of demand for transportation services.

Emphasis has been given to actions (1) and (2) and to a lesser extent, (3). TEP suggests energy-motivated R&D for (1) and (2) and recommends continued study of R&D options for (3).

The Energy Context

Historically, consumption of energy in the U.S. has doubled every 20 to 25 years. This trend of energy demand is projected to continue at least until the year 2000. Many groups are working to meet the projected demand. Nuclear energy supplies 0.2% of the demand now. The successful development of a breeder reactor technology is essential for nuclear energy to be able to contribute substantially as a source of energy in the future. The U.S. possesses massive reserves of coal and oil shale, but domestic production of both petroleum and natural gas has peaked and is inadequate to meet current demand. In 1971, the U.S. imported about 3.9 million barrels per day (mbpd) of petroleum, about 26% of total petroleum consumption. Without a change in Government energy policy, by 1985 imports are projected to increase to about 13 mbpd and account for about 53% of consumption. The Organization of Petroleum Exporting Countries (OPEC) has successfully negotiated to increase the price of petroleum.

Transportation as a Consumer

In order to meet the demand for transportation services, the transportation sector of the U.S. economy annually accounts for about 25% of the energy demand (111.7 billion gallons), more than 98% of it from petroleum. Highway vehicles consume about 82% of the energy used for transportation purposes; the remainder is consumed by aircraft, trains, pipelines, and domestic and international shipping. Passenger travel accounts for about two-thirds of the energy used by transportation with the automobile using about 85% and the passenger aircraft about 12.5%.

Projections to 1990 of the transportation demand and of demand for energy for transportation indicate that (1) transportation will keep its 25% share of total energy consumption (246 billion gallons), (2) the highway share of transportation energy will drop to about 65% (160 billion gallons), (3) the aviation share will increase to about 26% (64 billion gallons), and (4) the total marine (domestic and international) share will increase slightly but stay in the range of 5% to 6%. Further, simple projections out to 2020 indicate that highway vehicles will account for most of the energy used by transportation and the use by aviation will grow to equal the use by the automobile. These projections assume a continuation of economic growth of present transportation trends in modal split and that ways will be found to meet the energy demand. While these projections are subject to much uncertainty, they strongly indicate that for the next half century the various highway vehicles will continue to be the dominant energy consumer of the transportation sector, and that aviation will become an increasingly significant user.

The modes of transportation and different vehicles within the modes use quite different amounts of energy to accomplish the transportation purpose. The automobile typically provides 30 passenger miles per gallon (PM/G) while the airplane provides about 16 PM/G. Small cars provide about 48 PM/G, transit buses about 59 PM/G, intercity buses about 128 PM/G, and trains approximately 100 PM/G. For freight, trains provide about 190 ton-miles per gallon (TM/G), aircraft about 4, pipelines about 300, and trucks about 30. Large diesel combination trucks provide about 60 TM/G.

Remedial Actions

The transportation sector can affect the petroleum demand by any of the methods of (a) reducing demand, (b) substitution of more efficient means for less, and (c) improving efficiency. These methods may be applicable to the total transportation system, transportation modes, vehicles, and propulsion systems. Further, the promotion of electricity or fuels that are not derived from petroleum also contribute to the objective of reducing the dependence of transportation upon petroleum. Both technological and institutional actions may be used to obtain remedies.

Technological R&D

Technological improvements and changes have the potential to significantly reduce the projected energy demand, particularly the demand for petroleum, within the next 15 years and to permit the greater use of non-petroleum based energy sources by the end of the century. In the near term, within the next few years, it appears possible to demonstrate as much as a 30% reduction in fuel consumption by standard automobiles with 1976 emission controls without substantially affecting performance or losing the gains made in controlling emissions. This reduction in fuel consumption would be accomplished by using existing technology and optimizing vehicle and engine designs for that purpose rather than for lowest first cost, as is now the industry practice.

Low-loss tires, optimized engine-transmission combinations, turbo-charged engines, and reduced aerodynamic drag are among the changes that are expected to result in the reduced fuel consumption mentioned above. While the industry knows how to achieve substantial fuel savings at increased costs, the information is not in the public domain. Rational public discussion of the issue would benefit by having such information available. Demonstrating cars with reduced fuel consumption and evaluating the performance and cost trade-offs involved is needed. With half the car population so equipped by 1985, oil import requirements would be reduced by about 350 million barrels per year.

Alternate heat engines may also offer fuel economy advantages over the gasoline fueled spark ignition engine, provided that their present technical and economic problems can be brought under control by R&D efforts. Some of these advanced engines (for example, gas turbines, steam engines, Stirling engines, closed Brayton cycle engines) burn fuel continuously rather than intermittently and therefore have a multi-fuel capability. They could use liquid or gaseous fuels, and in some cases, could even use stored heat. These engines vary widely in their status of development. The earliest that they could be brought into mass production with accelerated development is estimated to be in the 1980's.

Looking further into the future, if ground transportation vehicles make substantial use of electricity, then a high performance battery is required. Such batteries exist only in the laboratory at this time and will require much time and money for their successful development. The consensus of expert opinion is that about 10 years or more are probably required to bring a high performance battery to the point where it could reliably be used in vehicles.

The projected increase in aviation and in fuel usage by aviation, coupled with the 10-year development cycle and the 20-year life of aircraft, makes additional attention to fuel consumption by aircraft more desirable. Technology now being developed holds promise of reducing fuel consumption by about 20 percent in the next generation of aircraft (circa 1985). The trend toward larger aircraft provides an opportunity to use cryogenic or nuclear fuels if they can be justified economically.

The TEP recommends that substantial emphasis be given to making transportation synthetic fuels with properties close to petroleum derivatives to permit undisturbed, continued use of the presently planned, petroleum-dependent transportation vehicle inventory.

The TEP has identified several new research and development efforts that appear to contribute significantly to the objectives of either improving fuel economy or promoting the use of diverse fuels. They are described briefly below and are discussed at length in subsequent chapters of this report. Definitions of R&D levels used are as follows:

Applied Research: Post-basic research, oriented towards solution of problems relative to specific and known needs of a system or subsystem.

Exploratory Development: Post research efforts directed to a preliminary assessment of a system or subsystem under development. Breadboard or bench hardware at full scale are tested and evaluated. From these, prototypes can be built (for engine development: tests through dynamometer and/or a single vehicle).

Advanced Development: Build, test and evaluate full scale prototypes. (e.g. 10 vehicles; 100,000 miles)

The new research and development efforts identified are:

AUTOMOTIVE	ESTIMATE TO COMPLETE
Fuel Economy Demonstration Demo 30% economy with up to four vehicle types, using state-of-the-art techniques.	$12 million over next few years
Heat Engine Development Plan to complete advanced development on the Stratified Charge, Lightweight Diesel, Advanced Gas Turbine, Rankine, and other external combustion engines.	$190 million over several years
Electric Battery Development Finish applied research enabling decision to continue with subsequent exploratory development of batteries (approximately $40M).	$10 million over several years
AIR	
Fuel Diversity Technology Conduct exploratory development for light and low-cost cryogenic tankage for new fuels and conduct combustor testing appropriate to overall future fuel definition.	$20 million over several years
AIR/MARINE	
Interagency Transportation Study Compare new transportation modal concepts with currently planned concepts to determine total economic impact, both for domestic and international commerce. Develop national transportation reference system model appropriate for use in assessing the overall impact of major modifications to the U.S. transportation system.	$5 million over next few years

III. TRANSPORTATION DEMAND PROJECTION

SUMMARY

The demand for transportation grows year by year much as the demand for other goods and services in our economy. The sources of traffic growth in our economy are population, income, local patterns, and the quality of transportation.

The Transportation Energy Panel (TEP) has made an extensive effort to review available data sources to confirm and add information to the transportation fuel consumption projections contained in the AUI* Reference Study.[1/] The modal administrations within DOT participated, and data from the recently completed "1972 National Transportation Study"[2/] has been integrated with their findings. General confirmation of the reference projections resulted, with some notable exceptions. Figure III-1 illustrates both the AUI and TEP fuel consumption projections. Figure III-2 compares AUI with earlier projections.

Good overall agreement of the AUI and TEP projections occurs because common data was used for the largest consumer, the automotive component--both automobiles and trucks. Further, neither of these projections includes any effects of substantially increased prices either of fuels or of vehicles. Differences between the projections involve primarily the following:

1. Air Mode Consumption. The reference projections show air mode saturation (constant fuel consumption per capita) to occur around 1990, whereas in the TEP projections, this will not occur until beyond 2000 because of assumed slower introduction of future supersonic air travel. The same saturation fuel consumption level is projected. However, it is noted that both projections beyond 1990 are probably conservative since transportation has followed GNP rather than population growth and the air mode has been growing faster than GNP in the past.

2. Bus and Rail Mode Consumption. TEP projects somewhat less growth in these modes based upon forecasts and economic considerations explained in the National Transportation Study.

[1/] See REF. 1.

[2/] See REF. 2.

*Associated Universities, Inc.

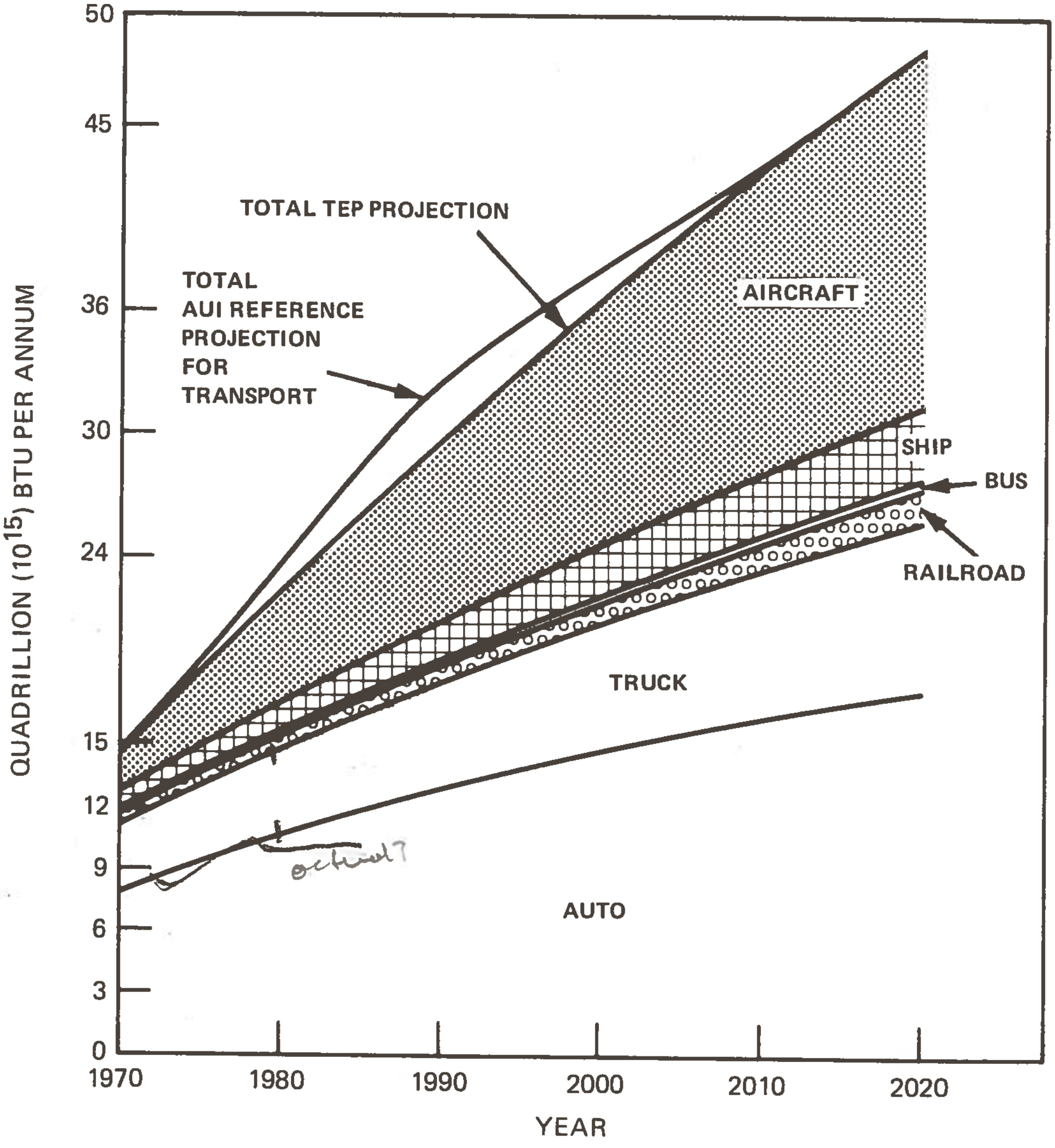


Figure III-1 - Projected Transportation Energy Consumption

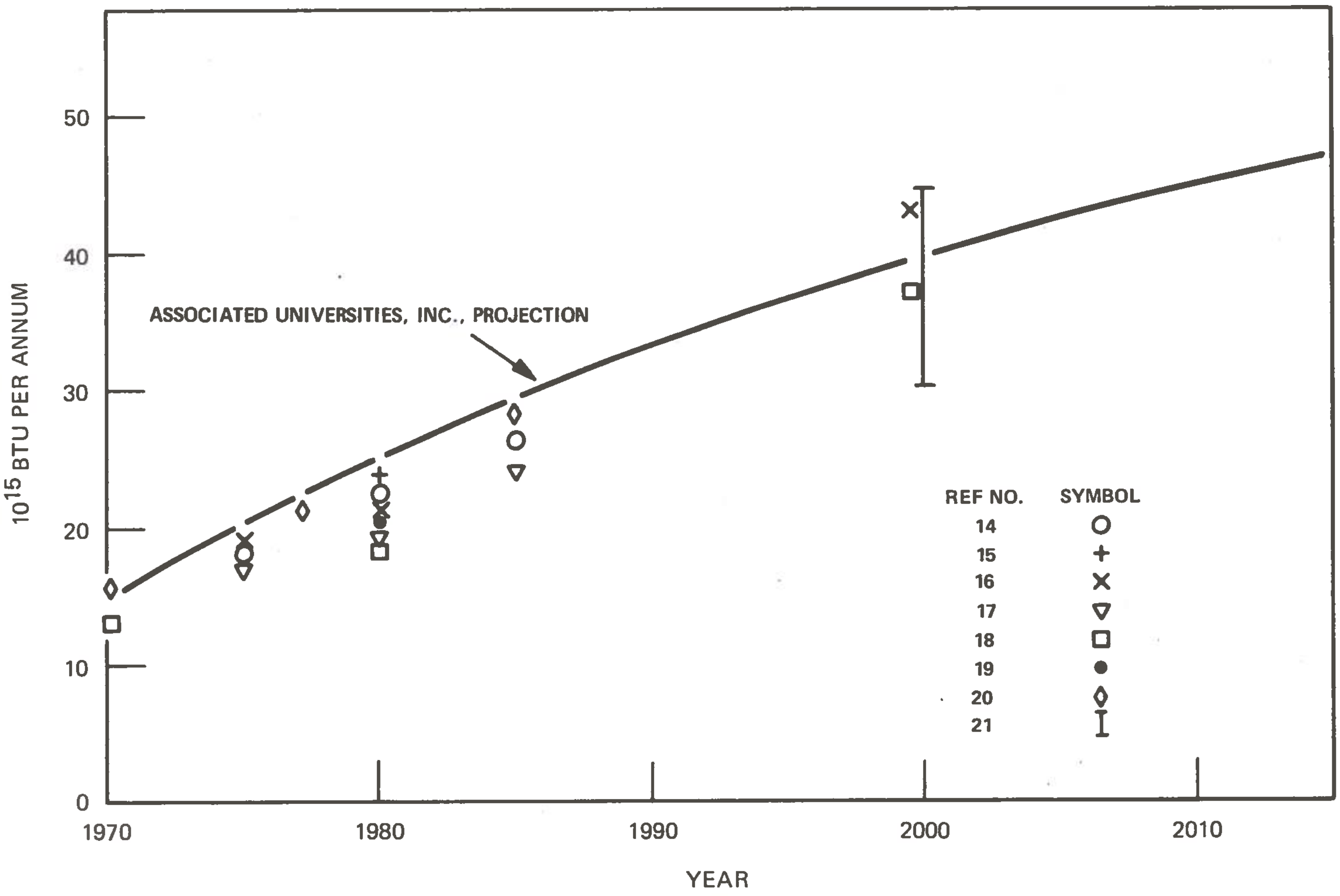


Figure III-2 - Transportation Energy Projection Comparisons

However, the reference projections--4.6% for bus and 3.7% for rail--in part represent the objectives of the Department of Transportation in that considerable current research and development is being expended to enhance and make more attractive to the public each of these fuel conservative and efficient modes of transportation.

3. Ship Mode Consumption. TEP projects growth at least double that of the reference projections for shipping, most particularly in international freight and recreational boating. The President, in his Merchant Marine Act of 1970, established the national objective to rebuild our maritime fleet to regain some of its former international strength. Currently, the U.S. flag carries only six percent of the total U.S. export and import tonnage, which is up from five percent in 1969. The Federal objective is to increase the proportion to 15% or so, and extensive maritime research and development has begun.

   It is further noted that by far the major portion of the fuel required to power these ships, both U.S. flag and other, is purchased outside of the United States and is not contained in the projection.

In addition to transportation demand projections, this section includes a brief summary of current Federal transportation R&D directed at developing technology to meet the future transportation capacity needs.

DISCUSSION

Transportation modal activities and cost projections from the National Transportation Study and fuel consumption data from the modal administrations are summarized in Table III-1 for the years 1970 and 1990, the time projection period of the Study. Activity is shown in passenger miles (PM) for passenger service and ton miles (TM) for cargo service. Average modal efficiency is shown as the activity divided by the fuel consumed. Total cost is shown from the Transportation Study. Total cost is taken as the sum of revenues and/or expenditures, as appropriate. Indirect costs such as environmental impact are not included. The cost data is projected in terms of constant 1969 dollars, so the average cost per unit transportation activity (PM or TM) is assumed constant at the 1969 value. The average cost per vehicle mile is 11.9 cents for the automobile.1/ The cost growth per annum is averaged over the 20-year period between 1970 and 1990. Finally, the data for each mode is described separately in the following paragraphs.

1/ See REF. 3.

TABLE III-1. U.S. TRANSPORTATION SYSTEM REFERENCE DATA

DATA[1] / MODE	1970					1990[2]				
	PM or TM[1] Bill	Fuel Consmptn Bill Gal	Average Modal Eff P/TM/Gal	Total Cost[3] Bill $	Average Cost Cent/P/TM	Cost Avg Growth %/Annum	PM or TM Bill	Fuel Consmptn Bill Gal	Average Modal Eff P/TM/Gal	Total Cost[3] Bill $
PASSENGER TRAVEL										
Auto	1920	64.2	30	88.2	5.4	2.6	3220	104.0	32	144.5
Aircraft	135	8.9	16	8.2	6.2	8.6	704	47.0	15	45.2
Bus	103	0.95	110	2.0	2.0	1.0	125	1.2	110	2.6
Rail	11	~0.11	~100	.45	4.1	0.0	10+	0.1	100	0.4
Other[4]	<20	1.5	<15	4.1	-	~7.0	<90	~4.5	~12	18.0
Subtotal	2190	75.7	-	103.0	-	3.8	4150	157.0	-	203.7
CARGO										
Rail	740	3.9	190	11.0	1.5	2.5	1223	6.5	190	18.2
Ship (Domestic)	529	1.6	320	1.4	0.27	3.3	1043	3.2	320	2.7
Truck[5]	491	16.7	30	47.1	9.6	4.2	1130	35.0	32	106.0
Pipeline	403	1.4	300	1.2	0.3	3.7	851	3.-	300	2.5
Aircraft (Domestic)	3	0.7	~4	0.7	22.5	11.6	33	9.0	4	7.7
Other[6]	-	13.2	-	32.8	-	~4.2	-	32.0	-	70.0
Subtotal	2200	37.5	-	94.2	-	4.2	4280	89.0	-	207.1
Total*	-	113.2	-	197.2	-	4.2	-	246	-	410.8

Notes:

1. Modal activity and costs from the National Transportation Study[2]; fuel consumption from AUI data.[1]
2. Projection uses 1.1% population growth and 4.2% average GNP growth.
3. The sum of total revenues or expenditures, as appropriate. Cost data is in constant 1969 dollars.
4. This includes business aircraft (.6 bill gal in 1970), general aviation (.1) and commercial boats and recreational boats (.8 bill gal).
5. Includes heavy duty trucks only; light trucking, delivery vans are in "other."
6. This category includes non-freight trucking (9.9 bill gal in 1970), international air freight (.5 bill gal) and international shipping (2.8 bill gal of U.S. fuel).

* Figures may not add due to rounding.

It is noted from the totals in the table that passenger and cargo transportation (not including international freight) are comparable in activity and cost; however, more than twice as much fuel is expended in passenger service than for freight. The modal growth figures show large growth in the air mode, more than double the assumed GNP growth (4.2% per annum) in this period, as well as continued strong growth in trucking. Saturation effects are felt in the automobile mode well before 1990, making room for the anticipated growth in per family air travel. Rail passenger service is projected to just maintain itself, largely due to the Federal commitment to do so. A similar situation exists with bus service; however, some growth is anticipated.

It is further noted that the total transportation fuel consumption is projected to continue at nominally 25% of the total U.S. consumption, and that total U.S. transportation expenditures are projected to continue at 20% of the GNP.1/

Automotive Modes

Highway vehicles consume by far most of the transportation fuel, and this has been particularly analyzed. Some of the relevant data is summarized in Table III-2, and the FHWA study is included in Technical Appendix I of this report.2/

Highway vehicles include autos, motorcycles, buses, and trucks. Non-highway vehicle fuel consumption, that is used by farm vehicles and the like, has not been analyzed per se; however, less than five percent of the highway consumption is attributed to that source.3/

The automobile consumes about 58% of all transportation fuel, yielding about 30 passenger miles per gallon (PMPG) for modal efficiency. A very large efficiency range within this mode exists however, as shown in Table III-2. Large autos yield about 29 PMPG, whereas small cars, such as Vegas, Pintos, Volkswagens, etc., yield 48 PMPG. Motorcycles top all with 83 PMPG. The trend towards the small car, currently so dramatic, will counteract increases in fuel consumption resulting from first-generation pollution control devices.

Automotive growth is projected at an average 2.6% per annum versus the 3.6% used in the Transportation Study. Historical travel data shows that

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1/ See REF. 2.

2/ See REF. 4.

3/ See REF. 5.

TABLE III-2. VEHICLE FUEL CONSUMPTION ANALYSIS - 1969

VEHICLE TYPE	FUEL	# VEHICLES MILLION	VMT BILL	FUEL CONSUMPTION BILL GAL	AVERAGE MPG	AVERAGE LOADING P OR T/V	PM OR TM BILL	AVERAGE MODAL EFFICIENCY
<u>PASSENGER</u>								
AUTOS		86.9	850	62.3	13.6	2.2	1869	30
SMALL	G	7.7	76	3.4	22.0	2.2	166	48
FAMILY	G	79.2	774	58.9	13.1	2.2	1703	29
MOTORCYCLES		2.3	9	.12	75.0	1.1	10.2	83
BUSES		.36	5	.95	5.3	20.3	102.5	109
TRANSIT	G/D	.07	2	.45	3.9	15	26.3	59
INTERCITY	G/D	.02	1+	.21	6.1	20.9	26.2	128
SCHOOL, OTHER	G/D	.27	2	.29	7.0	24.6	50.0	170
SUBTOTAL		89.6	864	64.4	13.4	2.3	1981	31
<u>CARGO</u>								
SINGLE UNITS		17	167	16.5	10.1	1.1	182	11
2-AXLE, 4-TIRE	G	12.3	119	9.4	12.6	.33	39	4
OTHER	G	4.4	43	6.4	6.8	2.5	109	17
	D	.3	5	.7	7.0	6.5	34	48
COMBINATIONS		.9	39	8.2	4.8	9.2	363	44
GASOLINE DRIVEN	G	.6	18	4.0	4.5	6.4	116	29
DIESEL DRIVEN	D	.3	21	4.2	5.1	11.6	249	60
SUBTOTAL		17.9	207	24.7	8.4	2.6	545	22
TOTAL		107.4	1,070	88.1	12.2			

[1] Data from FHWA analysis contained in appendix.

vehicle miles, number of motor vehicles, and fuel consumption have more than doubled in every 20-year period in the past. If growth continued at that rate, fuel consumption would exceed 130 billion gallons in 1990 for automobiles, consistent with the Transportation Study activity data. The lower TEP projections result, however, from the additional saturation emphasis resulting from linkage between number of persons of driving age and auto population and travel demand. Currently, there are 1.27 driving-age people per vehicle, having dropped from 1.49 in 1963. This is projected by FHWA to fall only to 1.16 in 1980 and level off at 1.09 in 1990. Further, the gallons consumed per vehicle are assumed to increase from 851 gallons per year in 1970 to 950 in 1990. The latter increase reflects limited anticipated additional mileage per vehicle year. Further discussion of these points may be found in the references.

Some of the automotive fuel consumed is due to traffic congestion. The 1972 Highway Needs Study1/ shows that urban land areas contain about 3% of the country, 74% of the population, 52% of the vehicle miles traveled, and about 14% of the roads. By 1990, it is projected that urban travel will increase 110%. To counteract the increasing trend toward traffic congestion caused by this projected travel demand, the FHWA has planned a definitive program of continued highway improvement over the next twenty years.2/ This plan shows a 10% increase in total road mileage, with a 64% increase to the urban highway network to retain smooth travel flow. The intercity network will remain essentially the same; only four percent additional mileage is called for. A parallel program called the Traffic Operations Program to Increase Capacity and Safety (TOPICS), is in effect to continually "reduce traffic congestion and improve operational efficiency by means of improved traffic control systems."

Regularly, urban areas across the land are reviewing their traffic situations, with Federal assistance as required, to determine what traffic control devices, in addition to other alternatives, are required to keep traffic flowing at cost-effective speeds. These studies are regularly being put together in order for urban communities to qualify for Federal funding under the TOPICS program. The primary benefit determination in these studies has been the savings in people's time, as opposed to fuel savings per se. To support the TOPICS program, FHWA has about $12M/year research and development activity to continue development of new traffic control systems, including:

1/ See REF. 6.

2/ See REF. 6.

1. Flow-actuated, computer-controlled urban traffic signals;

2. Freeway on-ramp traffic control and highway corridor traffic diversion systems.

As these new developments become available, they are added to the list of traffic flow improvement alternatives that urban areas may choose from.

An estimate was made regarding the current impact of traffic congestion on fuel consumption. The earlier mentioned report[1] contains data on the percentage of roads which are or soon will be rated deficient from a traffic flow viewpoint. Combined with other data in the report, it has been estimated that about five percent of the daily vehicle miles traveled occur in traffic-congested conditions. Assuming this congestion reduces the potential vehicle's mileage by two, a five percent energy impact results. Somewhat less is expected to be recoverable. However to keep the impact as low as it is, will require continued R&D in this area.

Trucks. Breakdown analysis of the truck fleet fuel consumption is also shown in Table III-2. As reflected in the column of data containing average loading per vehicle, the 2-axle, 4-tire vehicles include all the non-freight vehicles referred to in Table III-1. These vehicles are comprised of service and utility trucks, garbage trucks and the like.

The data shows that trucks have consumed about 39% of the auto fuel consumption; however, if the non-highway vehicles are classified as trucks, the 44% assumption in the reference projections may be justified. DOT projections[2] [3] show substantially more growth in trucking than in auto, motivated by the anticipated continued trend of urbanization by the U.S. public. This trend is projected to favor trucking relative to rail freight because urban freight is expected to gain with respect to intercity freight.

It is noted from Table III-2 that the large diesel-driven combination trucks provide 47% of the highway freight ton-miles while consuming only 16% of the total truck energy. This is due to their relatively good transport efficiency of 60 TMPG.

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[1] See REF. 6.
[2] See REF. 2.
[3] See REF. 4.

Buses. As is well known,[1] [2] the bus mode represents an extremely efficient mode of travel. Buses provided about 5% of the 1970 passenger service, using only 1.5% of the total fuel consumed in passenger travel. Bus service also provides low-cost travel. The average cost is shown less than half that of the auto. Specifically, the intercity bus revenues were about 3 cents per passenger mile, while the school bus expenditures were only 1.5 cents per passenger mile.[3]

It is further noted from Table III-2 that while the transport efficiency of the family car is about half that of the transit bus, the small car has a transport efficiency which is nearly comparable.

Less than one percent growth of this mode is projected without more Federal assistance.[4] [5] The Department of Transportation is currently conducting about $28M per year in research and development to develop overall bus technology [6] so that the past negative growth trends will be reversed. These efforts include:

1. New intracity bus development
2. Dial-a-ride bus demonstrations
3. Bus dedicated-lane demonstrations
4. Bus right-of-way traffic control systems

Military Travel Fuel Consumption. The Department of Defense has indicated use of approximately 15 billion gallons (2 quadrillion BTU's) per annum in 1969.[7] The AUI reference data includes 4 billion gallons for military aircraft, leaving about 11 billion gallons (7% of transportation fuel) not accounted for, for the military ground vehicles, ships, etc.

Aircraft Modes

Major growth in air travel and air freight has been experienced in the past--14% and 13% per annum respectively--averaged between 1965 and 1970.

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[1] See REF. 4.
[2] See REF. 8.
[3] See REF. 2.
[4] Ibid.
[5] See REF. 4.
[6] See REF. 7
[7] See REF. 9.

This is projected to continue, with per capita saturation effects not occurring as early as projected for the auto. The air and auto modal fuel consumption projections are shown in Figure III-3, including both the AUI and TEP projections. The AUI data assumes a more vigorous introduction of supersonic air travel and air travel demand in general. FAA projections show less immediate growth, with per capita saturation not occurring until beyond the year 2000.

The per capita saturation in this mode is projected at a constant level as done in the reference projections. However, in the past, total transportation activity has grown with GNP, not merely with population. This would indicate more growth in the non-automotive modes beyond 1990 if continued exponental growth in productivity is projected.1/

The vigorous projected growth in air travel, in a sense, results from the saturation effects in the automobile mode. It has been noted that people tend to spend a constant percentage of their disposable income or personal travel (like about one-sixth of it. In fact, records show travel expense percentage tends to grow slightly with income2/). Accounting for both the projected growth of GNP (4.2%) and population (~1.1%) indicates a 3% projected yearly growth in per capita travel expenses. Thus, saturating auto expenses leaves an excess for family travel which grows much faster than income does. Figure III-4 is included to graphically illustrate the anticipated auto saturation. The curve is based on 1970 income/auto statistics. Plotted on it is projected mean consumer-unit disposable income, using the 3% growth rate in disposable income per capita.

Referring to the AUI reference data, the 1969 fuel consumption breakdown for the air mode is 10.2 billion gallons of jet fuel for non-military air carriers, .6 billion gallons of gasoline for general aviation, and 4.2 billion gallons shown for the military. The first two check with available sources from the Civil Aeronautics Board (CAB). For the 1970 reference data in Table III-1, CAB data3/ of 8.9, 0.7, and 0.2 billion gallons of jet fuel for passenger service, domestic freight and business air (jet only) was used. An average air freight modal efficiency of 4.2 ton/miles per gallon was indicated and used for the 1970 air cargo estimate of 3 billion ton miles. For further reference purposes, the 1970 CAB data was analyzed by vehicle class, see Table III-3.

1/ See REF. 12.
2/ See REF. 2.
3/ See REF. 10.

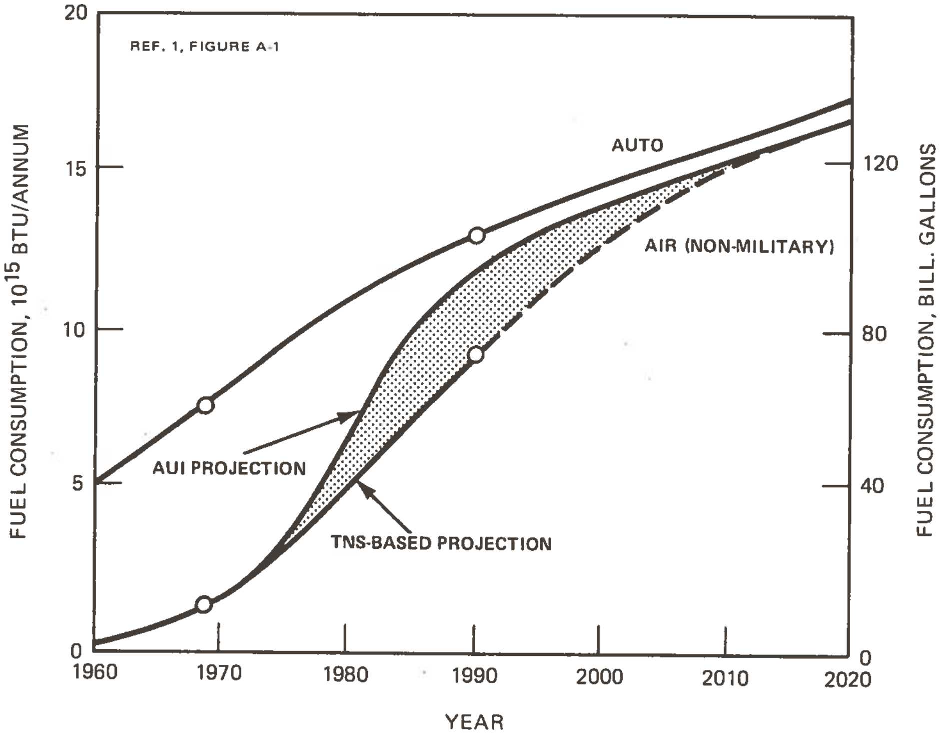

Figure III-3 - Auto and Aircraft Projected Fuel Consumption

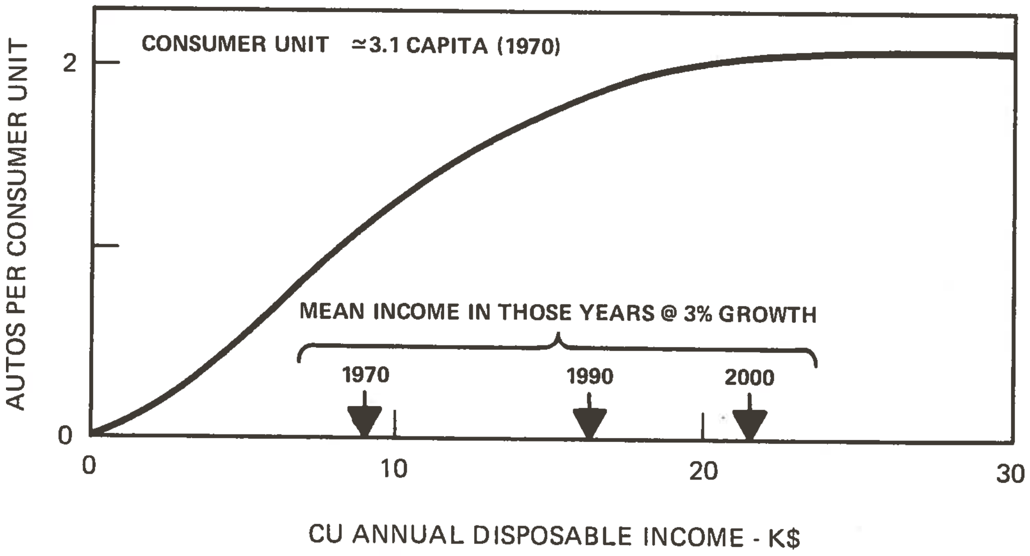

Figure III-4 - Auto Saturation Effects

TABLE III-3 AIRCRAFT FUEL CONSUMPTION ANALYSIS-1970

VEHICLE TYPE	FUEL	#VEHICLES	VMT BILL	FUEL CONSUMPTION BILL GAL	AVERAGE MPG	AVERAGE LOADING P OR T/V	PM OR TM BILL	AVERAGE MODAL EFFICIENCY
PASSENGER	--	2,541	2.27	8.92	.25	49.4	130.8	14.7
DOMESTIC-TRUNK	JP	1,449	1.52	6.11	.25	58.9	86.7	14.2
TURBOFAN	"	1,248	1.29	5.02	.26	59.3	74.1	14.8
TURBOJET	"	171	.22	1.07	.21	56.0	12.4	11.5
TURBOPROP	"	30	.005	.02	.29	39.2	.2	11.3
DOMESTIC-LOCAL	--		.26	.66	.40	34.8	8.2	12.5
TURBOFAN	"	183	.14	.45	.30	41.0	5.8	12.8
TURBOPROP	"	309	.11	.20	.57	21.0	2.3	12.9
PISTON	G	191	.007	.01	.75	16.0	0.1	12.0
INTERNATIONAL	JP	303	.38	1.78	.21	77.4	30.7	17.2
TURBOFAN	"	260	.32	1.45	.22	96.5	27.4	17.9
TURBOJET	"	43	.05	.25	.18	73.9	3.3	13.3
SUPPLEMENTAL	"	64	.09	.3	.28	50.0	4.4	14.0
GENERAL AVIATION	--	126,815	3.28	.70	4.69	2.1	6.6	9.5
SINGLE-ENGINE PISTON	G	108,704	2.24	.39	5.74	1.5	3.4	8.6
MULTI-ENGINE PISTON	G	15,882	.76	.14	5.43	3.0	2.3	16.3
TURBINE	JP	2,229	.28	.17	1.65	3.5	1.0	5.8
CARGO	JP	150	.24	1.00	.24	20.2	3.9	4.3
DOMESTIC-TRUNKS	"	99	.17	.70	.25	16.5	2.8	4.0
TURBOFAN	"	79	.15	.62	.24	16.7	2.6	4.2
TURBOJET	"	20	.02	.08	.39	8.8	.2	2.7
INTERNATIONAL TURBOFAN	"	44	.07	.30	.23	24.0	1.1	3.7

Air mode activity, costs, and projected growth are shown from the National Transportation Study.1/ Slightly reduced modal efficiency is indicated to account for probable introduction of VSTOL into the domestic passenger service and supersonic jets into international travel. The sum of both is not deemed likely to provide more than 10% of the total service and half the modal efficiency of these with respect to the current aircraft is assumed.2/ If all the 1990 international travel (180 billion PM or 25% of the projected service) is accomplished with similar SST aircraft, then 20% impact on average modal efficiency would result. However, the introduction of these aircraft will be counterbalanced by continued introduction of the more efficient jumbo jet aircraft, including 2- and 3-engine versions.

CAB aircraft cost data3/ give some perspective to the percentage of air travel cost represented by fuel and oil for commercial aircraft. For the average 4-engine turbofan aircraft in 1970, the fuel and oil cost was $191 per operating hour. This is about 14% of total cost, both direct and indirect. This corresponds to more than 22% for the automobile (consumer fuel costs less taxes). The difference is primarily due to the bulk purchase economies of commercial aviation (the average cost of jet fuel is given at 10+ cents per gallon).

Extensive R&D is being conducted by NASA and DOT (FAA) to accommodate the rapidly increasing air traffic demand. At NASA, about $40M of research a year is underway in Advanced Air Transport and Supersonic Air Transport Technology.

The FAA, on the other hand, is developing the air traffic control technology to meet this damnd. Peak frequency of takeoff and landings is expected to more than double by 1990, while the number of airborne aircraft within a major terminal hub may quadruple. To accommodate this, advanced control systems are being developed, including more accurate navigation systems, microwave landing systems to permit controlled landings in near zero-zero visibility, and multiple aspect approach systems for the airports. The FAA R&D effort is currently funded at the $75M level.4/

Rail Modes

Rail passenger service in 1970 was 6% of the total domestic passenger service, whereas the freight service was more than 33% (see Table III-1).

1/ See REF. 2.
2/ See REF. 8.
3/ See REF. 10.
4/ See REF. 7.

In terms of total cost, rail freight revenues represent 96% of the rail dollar. Past freight growth averaged .4% per annum between 1965 and 1970 (up from previous years), whereas the passenger service dropped 9.3% per annum.1/ The Transportation Study projects future growth at 2.5% for freight and an average breakeven in passenger service.2/

Freight revenues are projected as a whole to grow as the GNP does, but not ton/miles per se. A decline in relative importance of physical materials and relocation of economic activity to economize on freight requirements is forecast. Faster freight cost growth relative to ton/miles growth is foreseen because of a continued substitution of more costly intracity ton/miles for intercity ton/miles and a continued diversion of freight traffic to higher priced modes, namely truck and air freight.

However, more growth is foreseen than in the past because of new technology rapidly being implemented into the rail system, such as:

1. Unit trains - trains especially adapted to the needs of major freight customers, such as the fuel resources and automotive industry.

2. Containerized freight - wherein the freight interchange between the truck and rail systems becomes much more efficient, linking the future growth of both modes for intercity freight.

3. Computerized yard and interchange control - use of automatic car identification systems as inputs to computerized interchange yard control significantly speeds up the rail long-haul time.

The decline of rail passenger service is projected to stop because of the major Federal commitment to help do so. The Department of Transportation is currently expending, nominally, $100M in research, development, and demonstration to bring this about. Such efforts include the following:

1. Current Metroliner and Turbotrain demonstrations
2. Intracity rapid transit development
3. Intercity rail developments
4. Intercity high speed train developments (tracked air cushion and magnetic levitation)

1/ See REF. 2.

2/ Ibid.

The fuel division shown in Table III-1 has been estimated using generally accepted modal efficiencies for rail passenger service.[1] As is noted in reference projections, the electric load relative to the diesel fuel load is very small. The U.S. railroads operate about 27,000 diesels vs. 400 electric engines.[2]

Marine Modes

The reference data shows .91 x 10^{15} BTU's consumed in 1969 by "miscellaneous transportation (mostly ships)." The USCG has established the following breakdown for the marine modes:[3]

Figure III-5 1969 Marine Data

Submode	Fuel Consumption		TM or PM Billion	Avg. Modal Efficiency TM or PM / Gal.
	10^{15} BTU	10^9 Gal.		
Domestic Freight	.20	1.42	529	370
International Freight*	1.70	11.70	3000	256
Recreational Boats	.13	1.06	23	22

*Estimated data for both U. S. and foreign flag vessels.

The domestic fleet travels at nominally 6 knots and consists mainly of barges. The modal efficiency of 370 ton-miles/gallon is consistent with the domestic shipping industry's rule-of-thumb that one brake horsepower of propulsion is needed for every 3.5 tons of cargo. The total ton-mileage is established from records kept by the Corps of Engineers.

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[1] See REF. 2.
[2] See REF. 11.
[3] See REF. 12.

The international fleet is a combined fleet of U.S. and foreign-flag ships, with a predominance of foreign-flag ships. Currently, only 6% of the tonnage is carried by U.S. flag ships, up from about 5% in 1969. This fleet cruises at nominally 17 knots. The modal efficiency is not greatly reduced from the domestic fleet, however, because the ships are far more streamlined.

The Bureau of the Census publishes records on both U.S. flag and foreign flag freight tonnage, as well as total fuel sold to both in the U.S. The tonnage data combined with known international cargo distances indicates a total of 3000 billion ton-miles of freight transport for both imports and exports. The majority of this is general and dry bulk cargo (78%), and the balance is liquid bulk (primarily tankers from South America). The USCG estimates 11.7 billion gallons of fuel is required to carry the total tonnage, using average transport efficiencies as established in earlier marine studies. However, Bureau of the Census records show only 2.7 billion gallons (.37 x 10^{15} BTU's) sold in the U.S. Thus, about 77% of the fuel required for all U.S. international commerce is purchased outside the U.S.

The USCG Office of Boating Safety estimates that 1.06 billion gallons of fuel was used by recreational boating in 1969. The average modal efficiency is estimated at 22 passenger miles per gallon, representing a mean of 3.6 passengers per boat and about six boat-miles per gallon.

In summary, the total civilian marine fuel consumption from U.S. pumps in 1969 was .7 x 10^{15} BTU. This accounts, however, for only 20% of the fuel required for international freight transport. Further, the Department of Defense has grossly estimated that .5 x 10^{15} BTU additional was consumed by the U.S. Navy in 1969.

Expenditures for transportation on the Nation's waterways are projected to expand at an average rate of about 4.6% per year over the next 20 years.[1] Recreational boating is expected to nearly treble, while domestic freight is forecasted to double. International freight is projected by the USCG and others[2] to expand at more than double the rate assumed in the reference projections (2% per annum).

The Department of Commerce currently has underway a major research and development effort to bring marine technology to the point necessary to achieve a much larger share of the world market by the U.S. Merchant Marine. This effort has reportedly increased from about $7 million in FY 1969 to about $30 million budgeted in FY 1973.

1/ See REF. 2.
2/ See REF. 12.

IV. TECHNOLOGICAL OPPORTUNITIES AT LOWER POWERS

Lower power vehicles (mainly autos and trucks) presently consume about 74% of the transportation energy (all oil), and are projected to consume well above 50% by the year 2020. In view of this, the Panel assessed a wide variety of technologies which could have a favorable impact on fuel consumption and diversification (see Appendix I for detailed assessment). Three main areas were distinguished:

1. Technology for Fuel Economy.

2. Improved Engines and Fuel Diversification.

3. Electric Propulsion Technology.

For each area, the technology assessment and Panel recommendations are summarized.

TECHNOLOGY FOR FUEL ECONOMY

This is a group of technological measures[1/] which, if successfully implemented, could result in an estimated reduction by as much as 30% of the fuel consumed by autos and trucks.

1. Assessment Summary.

   Four technological measures are considered for substantially reducing the fuel consumption of autos and trucks.

   a. Aerodynamic Drag Reduction: It is well known that aero-drag becomes the dominant power consumer at speeds above 40 to 50 mph, depending on the vehicle. Typical aero-drag coefficients are given below, in units of lbs/ft^2-(mph)^2.

      "Teardrop," (most desirable, streamlined body): 7.5×10^{-5}

      Typical Autos, on the road today: 1.3×10^{-3}

      Typical Trucks, on the road today: 2.5×10^{-3}

      Flat Square Plate (most undesirable shape): 3.2×10^{-3}

[1/] Initially reported in Ref. IV-32.

There is a large margin for improvement. From the mid-thirties to the late sixties, there was a long series of technical articles[1] publishing results for truck and auto aero-drag improvements.

The cognizant group within the Panel has estimated that a 5% energy saving may be expected at very modest program cost for engineering development and at small cost for product acquisition by the customer. More substantial energy benefits, of 20% to 30% potential level, especially for trucks, will require moderate levels of R&D and production engineering. However, even under these conditions, the increases in new truck and auto acquisition costs are still expected to be modest.

A brief outline of the required R&D steps follows: Basic available analyses and technology should be restudied with reference to current vehicle designs and customer needs and attitudes. Experiments should be designed to rapidly quantify the "energy benefits," apparent impact on vehicle production costs, customer acceptance and other relevant "trade-offs." A logical sequence for experiments is: fractional scale model testing, followed by full scale mock-up tests. Then the most promising concepts should be tested on the road by actual operational vehicles, and "real world" fuel savings should be determined.

b. Rolling Resistance Reduction: Rolling resistance provides the dominant power demand at lower speeds, generally below 50 mph. for both autos and trucks. The principal contributor to this resistance (over 90%), is the friction provided by the loaded tires of the vehicle. Newer tire designs, in particular the steel belted radial ply tires, provide a substantial reduction of this loss. A reduction of this loss ranging from 15% on ice to 45% on sand is reported.[2] This may be translated into fuel economy in the vicinity of 5%-10% on the average road. In addition to this remarkable result, the newer design tires offer substantial advantages over the bias ply tires. For example, tread life improvements of 70% to 100% are claimed, better puncture resistance, better stopping ability, and improved drawbar pull. Such claims are supported by experimental evidence.
Current engineering developments are in their testing phases, in substantial vehicle sample sizes. For autos, the efforts are

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1/ See Refs. IV-1 to IV-25.

2/ See Ref. IV-32.

concentrating on verification of compatibility with existing suspension systems. Truck efforts concentrate on correlation of controlled experiments with in-service operational experience.

In the case of these new tire designs, there is very little R&D required. The verification of claims and the compatibility with existing auto and truck designs will soon be resolved.

c. Load to Engine Match: In all vehicles on the road today, except possibly for the large trucks, the engine-transmission driveline is not well matched to the actual vehicle road demand.

The power trains in use today are optimized for lowest manufacturing cost and possibly for greater convenience and ease of operation to the driver. The consequence of these practices is that the gasoline engine is forced to operate at varying part load and part speed points, off the optimum design points for minimum specific fuel consumption.

The Panel estimates that an energy benefit of 10% to 15% may be realized by a reoptimization of auto power trains. In most cases existing past technology may be recalled and refined for present applications. Refined designs can be obtained from laboratory prototype tests and these designs can be road tested in confirmatory projects. The incorporation of these reoptimized designs in production autos is estimated to increase the acquisition cost to the customer by $100 to $200.

d. Small Base Engine with Boost: This approach is essentially an alternative to the load/engine match discussed above. A higher load factor is imposed on the engine through design rather than through drive train modifications. Specifically, a supercharger or turbocharger is combined with a small base engine. The small engine is efficiently utilized for the routine demand and the supercharger assists the engine to negotiate peak power demands.

There is hardly much novelty in this idea and all the basic technology is at hand. However, for wide-range applications, a few additional steps are necessary. Thus, a turbocharger should be analytically matched to existing 4 to 6 cylinder engines, so that the equivalent power of naturally aspirated 6 cylinder or V-8's can be obtained.

Dynamometer test and design refinements are required. This should be followed by prototype development and tests, and by performance verification in large fleets.

The estimated energy benefit from this approach is about 15% in fuel savings. Net increased cost to the consumer for a 6 cylinder and boost, versus a plain V-8 engine of equivalent performance, is estimated to be $100 or less.

The assessment of the aforementioned fuel economy subtechnologies is summarized in Table IV-1, for the four most common vehicles on the road. For each vehicle we show the present energy consumption as a percentage of the total transportation energy. The last column shows estimated energy benefits grossly averaged over all types of vehicles. The entries "major," "moderate," and "minor" are a rough measure of the importance of a subtechnology for a type of vehicle and its driving cycle. For example, aero-drag reduction is much more important for the high speed intercity truck than it is for the urban service van.

Note that not all four subtechnologies give benefits which are additive in a straightforward fashion. Cases (a) and (b) are outright additive, but to this you may add either (c) or (d). Thus, by inspection of Table IV-1, we may conclude that a compound benefit of 25% to 30% can be realized by adopting cases (a) plus (b) plus either (c) or (d). If such a combination is implemented in mass production, the net increase of first cost to the consumer is estimated at $300 to $350. This increase could be offset in about three years, by the 30% fuel savings at present fuel cost. A progressively shorter offset period is naturally evident at progressively higher fuel costs.

The most important benefits arising from a full implementation of this technology are evident in the data tabulated below:

Projected U.S. Petroleum Demand: by 1985	9.4×10^9 barrels/yr.
Projected U.S. Petroleum Domestic Production: by 1985, including new discoveries--north slope and shale	3.6×10^9 barrels/yr.

TABLE IV-I SUMMARY OF APPLICATIONS OF FUEL ECONOMY MEASURES TO VEHICLES ON THE ROAD AND THEIR ANTICIPATED AVERAGED ENERGY BENEFIT

Vehicle Type / Fuel Economy Subtechnology	Family Car (31%)*	Commuter Car (21%)	Urban Freight Del. & Ser. Van (13%)	Intercity Freight Truck (9%)	Anticipated & Averaged Energy Benefit
a. Aero-Drag Reduction	Moderate	Minor	Minor	Major	5%
b. Rolling Resistance Reduction	Major	Major	Major	Minor	5%-10%
c. Load/Engine Match	Moderate	Major	Major	Minor	10% to 15%
d. Small Base Engine plus Boost	Major	Major	Moderate	Moderate	15%

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* See text, page 32.

Projected U.S. Petroleum Demand: for highway travel by 1985 (FHWA, Forecast 1971)	3.4 x 10^9 barrels/yr.
Fuel Savings, 30% (Full implementation of fuel economy technology)	1.1 x 10^9 barrels/yr.

Besides the obvious and substantial savings of a valuable and depletable natural resource, three additional points are quite important:

(1) The dollar value of the savings to the consumer is about $17 billion/year, estimated at 42 gallons/barrel and 36¢/gallon. These are 1971 dollars and assume that price of oil will remain constant. There is speculation that fuel cost might double by 1985.

(2) A strong favorable impact on the balance of payments may be expected, in view of the large discrepancy between the aforementioned U.S. demand and U.S. production of oil by 1985.

(3) The projected benefits are remarkable by comparison to the "minimum risk" and relatively trivial investment required for the preparation and implementation of the "Fuel Economy" technology. This technology could be incorporated into full production as soon as 1978, the first year dollar benefits exceeding $1 billion/year. This would increase steadily as newly produced vehicles become operational.

2. Recommendations.

Detailed recommendations may be found in Technical Appendix I, where the individual elements of this technology are evaluated and assessed.

A summary is presented here:

a. The Panel recommends that the matrix shown in Table IV-1 be considered in its entirety. Emphasis should be on the passenger vehicles (because of their larger share of consumption), but the van and the truck should be seriously considered (because they offer better changes of early implementation).

b. The Panel recommends Federal involvement in cooperation with industry (car, truck, tire, and associated industries), to precipitate an early preparation for the implementation of energy conservative technologies.

c. Recommended Program: In summary, a funding of $12M distributed over the next few years is considered adequate.

The first year effort includes technology reviews, analysis, and assessment of individual concepts, fabrication of prototypes, quantification of expected "pay offs," and design optimization of combined benefits. The second year includes design refinements as well as verification and demonstration of the expected fuel savings. Here the Panel suggests the initiation of "fleet sized" road tests with an intended total of 1 million vehicle miles, e.g., 10 vehicles at 100,000 miles, per type of vehicle. These tests and demonstrations (to be shared by most concepts under consideration), should continue into the third year of the program, as refinements are made, for a definite quantification of benefits.

d. In addition, the Panel recommends that the additional means be considered to activate energy conservative measures. The whole spectrum of alternatives should be considered including socioeconomic, regulatory, legislative as well as aforementioned technologically oriented measures. Moreover, factual information should be made available to the consumer, concerning fuel consumption and individual consumer operating expenses and savings, which could be expected from the alternatives recommended here.

IMPROVED ENGINES AND FUEL DIVERSITY

Beyond the near-term technology of fuel conservation measures, the Panel has attempted to assess improved heat engines and the use of fuels other than conventional. The improvements under consideration were assessed by comparison to the pre-1969 internal combustion engine (ICE), and to the anticipated 1976 ICE.

The technological opportunities for Fuel Economy are based on state-of-the-art technology, requiring only verification and demonstration to become available for implementation in a few years. However, the technology of improved engines is presently in exploratory development, with plans for advanced development. Improved engines are not expected to be available for production before the 1980's.

For orientation purposes, refer to Table IV-2 which summarizes the Panel's assessment of the expected potential of the prominent heat engine technologies at this time. Seven heat engines are tabulated and rated by comparison with the pre-1969 OTTO ICE. These are relative judgments based on expectation of projected R&D. Eight relevant parameters have been selected for the comparison, as listed on the top row of Table IV-2. For simplicity, the ranking for emissions, strategic materials, novel fuel compatibility and cost is given in four steps: Excellent (E); Good (G); Fair (F); and Poor (P). The motivation for selecting these engines for assessment is evident in the reference information. Briefly, the Stratified Charge (SC) Engine and the Light Weight Diesel (LWD), as a back-up, are potentially capable of providing acceptable alternatives to the energy extravagant 1976 ICE, in the early 1980's. The Advanced Gas Turbine, although still in conceptual design, promises substantial improvements over the aforementioned engines (SC and LWD), namely; better emissions, better first-cost to the consumer, and especially better compatibility with novel fuels, with small sacrifice in the other characteristics.

The Rankine and Stirling engines are external combustion engines with two significant advantages over the other engines: excellent emissions and excellent compatibility with novel fuels. Efficient versions of them for automotive application are still in a state of applied research. This is reflected by the mid-1980's dates for their production availability. The other advantages or disadvantages of these engines have large uncertainties due to their early developmental state.

The Wankel Engine has not been considered since its fuel economy is generally lower than the OTTO ICE and it requires much of the same clean up apparatus as the 1976 ICE. It is receiving much development attention by the automotive industry. Other engines also not specifically ranked herein include the Clawson, Feher, Johnston, and Warren Engines. These engines are in early states of development and should be evaluated along with various hybrid options in the supporting technology for continued heat engine development.

The following assessment summary provides data for the (a) Stratified Charge, (b) Light Weight Diesel, (c) Advanced Gas Turbine, (d) Rankine, and (e) Stirling Cycle Engines. In addition, an assessment of certain novel fuels is summarized in subsection (f).

TABLE IV-2. IMPROVED ENGINE PERFORMANCE BASED ON R&D EXPECTATIONS. COMPARISONS WITH ANTICIPATED 1976 OTTO ICE AND PRE-1969 OTTO ICE

	Fuel Economy[1/] MPG	Weight[5/] lb/HP	Emissions	Strategic Materials	Novel Fuel Compatibility	Projected Cost	Earliest[4/] Availability
1969 OTTO ICE	12[2/]	~3	P	E	F	E	Pre-1969
1976 OTTO ICE	~10[3/]	~4	F	P	P	G	1976
STRATIFIED CHARGE	13	~4	F	G	F	G	1980
LIGHT WEIGHT DIESEL	18	4-5	F	G	F	G	1982
ADVANCED GAS TURBINE	16	3-4	G	F	G	G	1984+
ADVANCED RANKINE	18+	4-6	E	G	E	G	1984+
STIRLING	18+	5-7	E	F	E	F	1984+

1/ Based upon a 4,300 lb. automobile driven over the Federal Emissions Urban Driving Cycle (see Federal Register Vol. 35-219, November 1970, Vol. II).

2/ Based upon EPA test data on unmodified 1969/1970 automobiles in this weight class.

3/ Based on a limited amount of unpublished EPA data from a 1971 Oldsmobile with 1976 emission control systems--8% EGR plus dual bed catalyst.

4/ To 10% of Annual Production.

5/ Specific weight of the prime mover excluding transmission.

1. Assessment Summary.

a. Stratified Charge Engine.

(1) Current Status.

Summary of Current Utilization: There is no current utilization.

Summary of Current R&D: Exploratory development has been in process for 5-7 years at Texaco Laboratories, Beacon, N.Y., and Ford Research Center, Dearborn, Michigan. During the past year, White Motors has built some 25 engines for Texaco who, in turn, has furnished these engines to car companies, both U.S. and foreign, under privileged agreements. The basic exploratory work has been technically sponsored and funded by DOD (Army) for the whole period with increasing EPA participation and funding in 1970-72. This exploratory phase is scheduled for completion by the end of 1972.

As the government-sponsored engines started to show promise in 1970 and 1971, industrially funded offshoots became visible. Perhaps the strongest effort has been and is continuing at Ford. That the Ford stratified charge (or PROCO Engine) is one of four R&D approaches to provide long-range solution to emissions requirements has been publicly reported at EPA hearings in both October of 1971 and April of 1972.

DOD Program plans for engineering development of this engine for Army trucks (1/4 ton or "Jeep") have been approved. Request for proposals were issued mid-June 1972. Evaluation of proposals, selection of Contractor, staffing and contract go ahead will be accomplished by end 1972. The overall plans involving vehicle engineering, substantial product improvements, formalized Army testing, et al., are targeted at initiation of engine production late in 1976.

(2) Ultimate Potential.

Effects on Resources: To achieve the 1976 emission levels, the 30% fuel savings over standard gasoline engines initially obtained will be traded back to a 5% to 10% savings. This compares to an expected loss of 20% to 25% from a 1968 uncontrolled level to 1976 compliance for standard engines. Thus, the fuel consumption of this engine should be at least 25% less than that of the 1976 ICE. Extension of utility of substantial portions of mass production tooling may be considered as an indirect but secondary conservation of resources.

Environmental Effects: The embodied feature of precise control of combustion offers lower fuel consumption at substantially reduced emissions levels. To meet 1976 standards cycle compromises and after treatment are still required, but dependency on add-on's is reduced. Compliance with 1976 emissions levels has been demonstrated in EPA Laboratories.

Economic Factors: The stratified charge engine is expected to cost $300-$500 more than a conventional gasoline engine at comparable emissions control levels. The operational fuel cost savings are expected to be $100(including tax), or $66 (excluding tax) per year. Consumer breakeven would occur in about 3-5 years. If gasoline price doubles, then breakeven is reduced to the 2-3 year period.

The premium cost of the stratified engine compared to the conventional gasoline engine is primarily associated with the addition of a moderate pressure injection system. The cost of the injection system is in the $1-$2 per hp/range for engines in the 100-200 hp sizes. Since the treatment devices of EGR* and catalytic reactors will be essentially the same for stratified charge and conventional engines at comparable emission levels the incremental cost will primarily depend on cost of the fuel injection system vs. the displaced carburetor. There is a concern that cost of the 1976 "sophisticated" carburetor could increase substantially over the 1970 cost. If the carburetor cost should increase from a $25 level to a $100 level, then cost premium of the stratified charge engine would be reduced toward the $150-$350 level. Production cost for the stratified charge engine should be accurately forecast early in the engineering development cycle.

The impact of introducing this engine on the economic system is considered modest to moderate. It will look like a Diesel engine but its internal loading, structural

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*Exhaust Gas Recirculation

strength and production tooling will be more like today's gasoline engine.

(3) R&D Requirements.

A pilot program is being sponsored by DOD (Army, to provide a clean engine for the Army 1/4-ton truck). This program is aimed at low annual rates up to 10,000 engines. Expansion or extension of this base program to provide meaningful demonstration in passenger cars is indicated. Partial information indicates that at least Ford is already headed in such a direction.

Time Scale for R&D: The planned Army program for Advanced Engineering Development has the ambitious goal for completion in about 40 months. Whether or not this goal can be achieved is a question. There are opinions in engine and car companies that the 40 months is optimistic and a more realistic time is 50-60 months.

Funding Estimates: The preliminary estimate for the Army Advanced Engineering Development of one concept of the stratified charge engine is about $17 million. This is for basic engine work on a small (4 cylinder - 175 cu. in.) engine and does not include funds for concurrent vehicle engineering and extensive vehicle testing. A back-up program to provide a parallel effort at a second contractor during the highest risk phases is estimated to cost about $2 million per year for two years.

Specific Considerations: The Army program will result in a militarized engine at the nominal 85 hp level. It will include features such as waterproofing for fording, 24-volt electrical system for communication, and 60% slope oil pan and provision for temperature extremes (-65°F to 115°F) which are not directly applicable to passenger car application. If the engine concept is considered a substantial candidate for passenger cars, then major Advanced Engineering Programs are required, aimed at the 150-200 hp size with features (accessories, et al) tailored for car application and mass production rates of hundreds of thousands per year. Historically, such commercial programs have cost about $30 to $50 million.

Difficulties and Uncertainties: The principal uncertainty is that experimental evidence is not yet available to establish durability and degree of emissions control degradation over 50,000 miles. The press of time has required telescoping of engineering development programs at substantial risk to investment prior to completion of exploratory work.

The addition of a moderate pressure fuel injection system to a standard gasoline engine does add complexity and could affect reliability and durability. On the other hand, a well-designed injection system should hold factory adjustment and be less susceptible to owner tampering than a sophisticated carburetor. Such comparisons warrant careful attention.

b. Light Weight Diesel.

(1) Current Status.

Summary of Current Utilization: Today in the United States a lightweight Diesel weighs a little over 1,000 lbs. in the 200 hp size, or at the specific weight of 5 lbs/hp. Gasoline engines for cars are at the 3-4 lbs/hp level. DOD (Army) R&D efforts have resulted in special attention to reducing weight and increasing power. These engines at higher power are well-advanced in Engineering Development with specific weights of 3.1, 3.6, and 4.2 lbs/hp in sizes of 640, 480 and 320 hp. Extrapolation of this demonstrated technology from the nominal 500 hp size to passenger car 150 - 200 hp appears to be straightforward with minimal technical risk.

Summary of Current R&D: Primary efforts to reduce weight in the Diesel engines seem to have been sponsored by DOD. Power, weight and space claim are major factors in combat vehicle. Major commercial efforts have not been evident, most likely because weight and space claims have not been dominant considerations in the truck and off-road construction vehicle market.

(2) Ultimate Potential.

Effects on Resources: The lightweight Diesel engine will probably meet the emissions requirements without suffering the 20% to 25% fuel consumption penalty expected for the gasoline engine. Further, the diesel is basically more efficient than the spark ignition engine with its higher operating compression ratio; hence it is anticipated that about half the 1976 OTTO ICE specific fuel consumption will be achieved by this engine.

Further, the Diesel engine inherently has a broader tolerance for the kerosene type of fuels. Hence, the demand on low- or no-lead gasoline at higher octanes and the burden on refineries would be relieved.

Environmental Effects: Diesel engines are or can be low on smoke, HC and CO. NO_X is a problem amenable to control within the basic Diesel engine because fuel delivery (already precise by the injection system) and combustion control (intra-cylinder turbulence and flow) are well-managed and subject to reoptimization for NO_X reduction. It is forecast that emissions requirements will be met by Diesel engines with less complex aftertreatment than required by the 1976 OTTO cycle.

Economics: Diesel engines cost more than car gasoline engines because they have high pressure injection systems, frequently utilize turbochargers and are designed for heavier duty (higher load factor) operation and much longer life expectancy.

Also, annual production rates of diesels are lower than SI's. Traditionally (prior to emissions controls), the 200 hp diesel would cost 2 to 3 times the car engine. If diesels were designed to passenger car engine practice and produced at 10 million vs. 10 thousand annual rates, the incremental acquisition cost will be due to the fuel injection system and minimal add-on treatment as compared to the carburetor with lots of add-ons. The incremental cost could be reduced to zero or in the worst case be $1-2 per hp greater for diesels. This difference converts to a comparable diesel acquisition cost of $300-$500 more than for a gasoline engine. Forty percent annual fuel savings would return to the consumer $160 a year (including tax), or $110 (excluding tax). Therefore, payback might occur in two to three years.

(3) R&D Requirements.

The R&D steps recommended include:

(a) Develop preprototype engines for dynamometer tests which have acceptable weight, emissions and noise levels for automobile use while simultaneously yielding high fuel economy.

(b) Integrate the technologies and know-how of gasoline engine and Diesel engine manufacturers.

(c) Build pilot quantities of engines and conduct extensive pilot vehicle tests.

(d) Stimulate major suppliers of fuel injection systems and turbochargers to participate and plan a times ten production capacity expansion.

Time Scale for R&D: The steps suggested above are for engineering development involving scaling and integration of available technologies. About four years is a minimum time estimate for engineering development to establish greater confidence for production in the broader range of 5-10 years.

Funding Estimate: Each lightweight diesel car program is expected to cost some $30-50 million of R&D funds.

Difficulties and Uncertainties: Perhaps the major uncertainty is consumer acceptance of the Diesel engine with its characteristic higher noise, odor, and cold starting sensitivity. There are no major technical difficulties forecast.

c. Brayton Cycle (Gas Turbine).

(1) Current Status.

Summary of Current Utilization: The Brayton cycle engine is used in all jet aircraft, turboprop aircraft, auxiliary power units, experimental and test automobiles, many high speed boats, and some small ships. The technology is well known.

Summary of Current R&D: Test automobiles with gas turbine engines include those by GM, Ford, Chrysler, and by Williams Research Inc. for American Motors. Progress has been made towards overcoming the fuel economy limitations of the earlier models, but 1976 NO_X emission levels are still to be achieved.

EPA research is underway to solve the technical problems facing introduction of the open cycle "free turbine" version of the Brayton cycle gas turbine to the marketplace. This approach builds on previous work of industry in developing the gas turbine for the automobile. In their Advanced Automotive Power Systems (AAPS) program, several teams of technical specialists are competing for solutions to problems such as high NO_X and high cost of manufacturing processes and of materials. The gas turbine produces very low HC and CO emissions (lower than the standards) without aftertreatment.

The results of this problem-solving research will be applied to automotive type gas turbines for performance improvements as determined first in the laboratory on engine dynamometers and then on the road in gas turbine vehicles. The award of an important test-bed engine contract is expected.

ARPA is sponsoring exploratory development of the all-ceramic turbine engines by Ford, in attempt to achieve high turbine inlet temperatures needed for improved fuel economy with this engine.

NASA has been conducting design studies of closed and semi-closed cycle Brayton engines for automotive application at the 400 hp level and higher. In the past decade, NASA has developed several closed cycle engines below 200 hp for on-board electric power generation in spacecraft. Preliminary study results indicate fuel consumption as low as .4 lb/hp-hr is obtainable--competitive with the Stirling cycle. Major problems exist, however, in achieving weight and size for automobile use as well as material cost limitations.

(2) Ultimate Potential.

Effect on Resources: R&D planning within the AAPS program anticipates better than 16 mpg fuel consumption for the family sedan with advanced versions of the open cycle gas turbine. This assumes recommended new developments are successful in getting the turbine inlet temperature to 2200°F, as well as obtaining greater efficiencies in auxiliary engine components. Some members of the TEP anticipate great difficulty in reaching this goal.

The continuous combustion characteristic of the turbine gives it a multi-fuel capability superior to the intermittent combustion engines as described in Technical Appendix I.

(3) R&D Requirements.

The R&D steps needed to achieve a clean and efficient advanced gas turbine for the automobile are (1) to complete the current AAPS development program to develop technology to meet the 1976 emissions standards and (2) to start development of an advanced gas turbine. The following development goals have been outlined by AAPS program staff as being appropriate for obtaining the latter objective:

(a) Increase the turbine inlet temperature to 2200°F or more, by use of new ceramic materials or improved wheel cooling techniques.

(b) Improve both turbine and compressor efficiencies by 3 to 4 percentage points with better aerodynamic designs.

(c) Improve regenerator and recuperator efficiencies by five percentage points or more by increasing their overall heat transfer effectiveness.

(d) Continue advanced transmission development to obtain improved load-to-engine matching.

One of the most difficult problems for the gas turbine is NO_X reduction. Techniques for reducing NO_X to acceptable levels already have been demonstrated in the AAPS research effort and these are now being engineered to be compatible with the AAPS test-bed turbine engine. It is emphasized that NO_X reduction and control take place in the combustion process and aftertreatment is not required. Much of the work on manufacturing cost reduction has now been started. Low cost regenerator materials and improvements in nozzle and turbine wheel manufacturing techniques are included in this work.

d. Advanced Rankine Engine.

(1) Current Status of Technology.

Current Utilization: Closed Rankine cycle engines, with water as working fluid (steam engines) are the principal type of heat engine used for stationary power plants. They also are used on large vessels. Both open and closed cycle steam engines have been used to power automobiles in the past but in the past but have been discontinued.

Current Research and Development: EPA's Advanced Automotive Power Systems (AAPS) program is sponsoring the development of three types of closed Rankine cycle engines for automobiles and the development of new technology to solve problems of weight, bulk, freezing, poor fuel economy, excessive condenser sizes, etc. The EPA program is planned for $25 million over a four-year period ending in FY 1975. EPA's technology development projects have shown the way to substantial improvements in Rankine cycle engines. The primary systems contractors of EPA are Steam Engine Systems, Thermoelectron Corporation, and Aerojet General.

The development is in the pre-prototype phase. A pre-prototype system consists of components designed to meet the performance goals of the prototype system which will later be installed in a vehicle for test and demonstration; however, the configuration, size and performance of each preprototype component may not conform to all the specifications required on the final installation in the vehicle. Emissions and performance testing of the three versions of preprototypes on engine dynamometers will commence in November 1972 and will be completed by April 1973. These tests will provide the first data on the system efficiencies, and on the extent that future engine and component development will be needed to meet design specifications for the vehicle application. The three competing systems will be narrowed down to two by June 1973, based on evaluations of the preprototype test results. At that time, the next phase of development--the prototype phase--will commence. Demonstration of the best of the two remaining prototypes will be made in automobiles in 1975.

Major technical problems associated with Rankine system development appear to have been successfully solved although confirmation awaits preprototype system tests. Some of these problems include: large condenser size, difficulty of providing lubrication at high steam temperature, and high exhaust emissions. Difficult problems in each of these areas were found by the General Motors Corporation when they built and tested a Rankine cycle power plant in 1969. For example, they found that the exhaust emissions from their steam engine were higher than those measured on the conventional engine.

Advances have been made in these and other areas. A new high efficiency heat transfer surface has been developed for the condenser. Regarding lubrication problems, recently completed durability tests on steam expanders show long lasting lubrication has been achieved in the currently severe design conditions of 1000°F and 1000 psi. This is significant because the GM steam engine design was limited to 700°F and 800 psi by lubrication requirements. This was a major reason for the poor fuel economy of that engine. Lastly, tests consistently show combustor emissions lower than needed to meet the 1976 standards, without exhaust after treatment. Thus, combustor technology has also been considerably advanced.

(2) Ultimate Potential.

Effects on Resources: Advanced versions of the Rankine cycle engine offer the promise of considerably improved fuel economy compared with the conventional engine. For example, the current designs of the AAPS's steam engine (steam, reciprocating) are expected to yield 13 mpg for the family sedan, while simultaneously meeting the 1976 emission standards. Further, proposed advanced engines may exceed 20 mpg (AAPS data).

Also, the ability of the Rankine cycle engine to use various fuels is a potential advantage.

Introduction of the engine into mass production would have a sizable impact upon the automobile industry. The nature and magnitude of the impacts of mass producing the Rankine engine with organic working fluid are being studied by International Research and Technology under contract to DOT.

Economics: The first cost of ownership for mass produced engines is expected to be larger than that of present day spark ignition engines meeting the 1976 emission standards.

(3) R&D Requirements.

The R&D steps to achieve an advanced efficient Rankine cycle engine for the automobile include first, completing the current AAPS efforts to develop technology for meeting the 1976 emission standards with reasonably good fuel economy and secondly, begin development of more advanced technology to achieve high fuel economy. New development tasks to accomplish this are indicated in AAPS advanced planning. These are:

(a) Increase the boiler operating temperature from 1000°F to 1300°F by further development of low-cost high temperature materials.

(b) Develop advanced designs of a "radial outflow impulse vapor turbine " to get 80% or more turbine efficiency; thereby achieving significant weight reduction for the system as well as fuel economy.

(c) Develop load-adaptive operating modes for the engine for improved part-load efficiency.

(d) Develop organic fluids with greater than 850°F operating capability.

(e) Continue advanced transmission work to further match output load to optimum engine speed characteristics.

e. Stirling Cycle Engine.

(1) Current Status of Technology.

Current Utilization: Several types of Stirling engines have been developed and used for small stationary power sources over the last century. Stirling-cycle devices, such as refrigerators (cryogenic), currently have highly successful applications. The Stirling engine has received much development in sizes up to 400 horsepower per cylinder by Philips Gloeilampenfabricken (Netherlands). United Stirling of Sweden is planning establishment of a production line for a 200 horsepower commercial vehicle engine.

Current Research and Development: Development work on truck size Stirling engines is being carried out in Germany. Recently, Ford Motor Company has joined with Philips for the purpose of developing the Stirling engine for the passenger car application.

The most recent research by Philips concerns an engine in the exploratory development stage which is compact and lightweight (less than five pounds per horsepower). It is expected to have exhaust emissions well below the 1976 standards, perform much like a standard engine, and have excellent fuel economy. It probably will be expensive. The design is backed up by experimental tests of some of the analytical results, specifically the projected low emissions of oxides of nitrogen.

The engine design is a major departure from earlier Stirling engines (employing rhombic drive). It is most easily described as a four cylinder in-line engine that has been pulled into a circle so that the first and fourth cylinders are adjacent. The crankshaft is replaced by a swashplate on an axle parallel to the center lines of the cylinders. The cylinders are interconnected to permit the working gas (nine grams of hydrogen) to flow from one to the next. The piston in each cylinder plays a dual role, as the power piston and as the displacer piston of the more familiar rhombic drive version.

(2) Ultimate Potential.

Place Within the System: The Stirling engine is somewhat better than the Diesel engine in terms of fuel consumption. Its advantage is especially significant in applications where a large amount of running time is spent at reduced output, or at idle.

The Stirling engine efficiency has been found by Philips to vary only between 40% and 34% from full power to 1/10 power.

The low fuel consumption is partly a consequence of the unusually wide temperature drop over which the closed gas cycle engines can function, the good cycle efficiency, and the practicality of a high degree of regeneration or recuperation over this drop. It is also due to the fact that efficiency can be kept high over a wide range of power outputs, and that starting is easy and idling for long intervals is not necessary.

Other advantages include a reduction in pollution products below currently required standards without loss of fuel economy and substantial noise level reduction with respect to the other engines.

Economics: Although first cost is projected higher than current engines, lifetime costs should be less due to reduced maintenance and fuel consumption, longer life, and fuel diversity.

The prototype conceptual design discussed earlier contains seven pounds of nickel or so, sufficient to potentially cause a supply problem for engines in large quantity. The trade off between materials versus performance of the engines needs to continue.

Environmental Effects: The potential pollution reduction with this engine is very significant. Philips has experimental test data, discussed in the literature.

(3) R&D Requirements.

A preliminary estimate has been made that $15 to $20 million over a three-year period is required to accomplish the development effort producing as an end product a prototype Stirling cycle engine demonstrated in a U.S. family sedan which meets the Federal Standards of 1976.

f. Novel Fuels.

The Panel defines "novel fuels" as fuels other than petroleum derivatives. In other words, gasoline or diesel fuel derived from shale, coal, or by any other means, is not considered a "novel fuel." A data summary relevant to lower power vehicles, in particular for the case of the full size passenger auto, is provided here.

These results are summarized in Table IV-3, where most of the relevant properties of certain novel fuels are compared to gasoline. The novel fuels under consideration are listed on the left column and each one is rated relative to gasoline. Methane and methanol have been chosen as typical examples of relatively simple derivatives from coal. Propane and ethanol are examples of less straightforward coal derivatives. Hydrogen might be produced from nuclear energy (either by electrolysis or by more efficient thermochemical schemes, if successful). Finally, magnesium hydride, ammonia and hydrazine have been included as examples of chemically stored hydrogen. Other possibilities of chemically stored hydrogen have been tentatively discarded. The alkaline hydrides such as the lithium, sodium, calcium and strontium hydrides are too expensive to produce, react vigorously with water, and some ignite spontaneously in air. On the other hand, the metallic hydrides, which are of interest because some of them take up huge quantities of hydrogen, are logistically unattractive because they require rare metals, e.g., palladium.1/

This section summarizes the novel fuel assessment from the combustion point of view without reference to specific heat engines. The entries in the first two columns of Table IV-3, namely gallons/BTU and lbs/BTU, are data from standard tables, normalized with respect to gasoline. These numbers are useful in providing a very quick rating. However, more informative are the numbers appearing under the columns labeled "Weight" and "Bulk." These are the weight and the volume estimated for the novel fuels and their tankage, necessary to provide a full performance family auto with a range comparable to that provided by 18 gallons of gasoline. A heat engine with the same efficiency is assumed in all cases. The fuel plus tank weight is higher than for gasoline, but nevertheless tolerable in most cases, except perhaps liquid hydrogen plus oxygen and magnesium hydride.

More serious difficulties are evident regarding the bulk of the fuel plus tank. The three cases of hydrogen appear to require unacceptable volumes for a passenger car. Large uncertainties in these volumes arise from the many assumptions and design tradeoffs to be made regards the cryogenic hardware and hydride fuel tankage.2/

1/ Most of the aforementioned novel fuels have been assessed from the electrochemical point of view (applications in Fuel Cells), in the Electrochemical Workshop of the Panel. The results may be found at the end of Technical Appendix I.

2/ See REF. IV-33 for further information.

TABLE IV-3 RELATIVE PROPERTIES OF

CERTAIN NOVEL FUELS FOR REFERENCE PURPOSES

	Gallons per BTU	Pounds per BTU	Weight lbs	Bulk cu. ft.	Fire Hazard	Toxicity	Combustion Rating	Distrib. Logistics	Tankage Cost
	(normalized)								
Gasoline	1.0	1.0	125	3	F	1-2	G	E	E
Methane (Liq.)	1.6	0.9	210	5	F	0-1	E	F	F
Propane	1.1	1.0	185	4	F	0-1	E	F	G
Methanol	1.8	2.1	250	6	G	1-3	G	F	G
Ethanol	1.4	1.6	180	3	G	1-2	G	G	E
Liq. Hydrogen	3.9	0.4	150	>13	P	0	G	P	P
Liq. Hydr/ Liq. Oxyg.	5.7	3.6	550	>18	P	0	E	P	P
Magnesium Hydride	4.1	4.9	700	>14	P	0	E	P	P
Ammonia	2.0	2.3	300	7	G	3	P	P	F
Hydrazine	1.6	2.3	265	5	E	3	P	P	F

Next the question of fire and explosion hazard is examined. A rating is presented in four steps: Poor, Fair, Good, and Excellent. The ratings are compounded judgments based on considerations of data regarding: flash point, autoignition point, vapor pressures, heat of vaporization, and explosion limits. Toxicity ratings appear in the next column. These are standard ratings as follows: (0: no harm), (1: slight but reversible harm), (2: moderate harm; could be irreversible), and (3: severe; could be fatal). Wherever two numbers appear, the first refers to inhalation and the second to ingestion.

The combustion rating is a very rough measure of the thermochemical properties of the fuel, including considerations of combustion (mainly in internal combustion engines), corrosion, and exhaust products. As may be seen, ammonia and hydrazine are rated poor mainly because of their corrosive properties in combustion. The hydrogen/oxygen combination is rated excellent because of its extraordinary zero pollution potential. Methane and propane, as lower hydrocarbons, are rated excellent only by reference to gasoline or the alcohols.

The next column in Table IV-3 deals with the logistical problems of central storage, distribution, and local storage of the novel fuels before they are stored in the automobile. These ratings are quite important in providing a rough idea of the potential deviations from the status quo. Thus, gasoline is rated excellent and only ethanol is rated good, since it requires comparable storage space per BTU, without any undesirable characteristics, on other counts. This means that ethanol could replace gasoline without appreciable modifications in the fuel storage and distribution logistics. By contrast, methanol is rated only fair

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1/ See Refs. 30, 31.

2/ See Ref. 29.

since it requires almost twice as many gallons/BTU as gasoline. This means that fuel stations and distribution trucks would have to double their storage capacity. The hydrogen cases are rated poor for automotive application, mainly because their distribution represents a major departure from the present fuel distribution system. (Explosion and fire hazard considerations are also relevant.) Ammonia and hydrazine are rated poor mainly because of their poor toxicity rating but also because of volumetric considerations. Finally, liquid methane, although in very limited application today, is rated poor in comparison to propane, which does not require cryogenic storage.

The last column in Table IV-3 summarizes information regarding the cost of the tankage and other handling hardware for storing the novel fuel onboard a passenger car. Gasoline, naturally, receives an excellent rating and so does ethanol, because it is not appreciably different. Propane and methanol are relatively good but not excellent, since the first requires a moderately pressurized tank (about 100 PSI), while the second requires a tank almost twice as large as a gasoline tank, for the same BTU content. Cryogenic hydrogen requires expensive hardware and is rated poor, while cryogenic methane is rated fair, since it requires less sophisticated cryogenics. Ammonia and hydrazine are rated fair, mainly because of special precautionary measures, which might be required to deal with their toxicity.

In view of the results of this very simplistic assessment, the Panel feels that ethanol ranks second with gasoline or other related petroleum derivatives for automotive application, from a transportation point of view. The first choice is to derive synthetic gasoline from shale, coal, or by any other means, provided that it is economically competitive with gasoline. Secondly, ethanol should be considered as an alternative fuel, if it can be made economically competitive.

Propane, methanol, and liquid methane follow in that order. Cryogenic hydrogen, hydrogen/oxygen and magnesium hydride appear relatively unattractive. Furthermore, ammonia and hydrazine are more unattractive. These last two fuels are basically hydrogen storing compounds. Their unacceptable combustion rating may be avoided if these compounds are treated for hydrogen extraction, before combustion. However, this adds complexity bulk, weight, and cost to the system. Besides, the poor toxicity rating of these fuels is still a serious problem.

2. Recommendations.

In view of the presented assessment summary, the Panel makes the following recommendations:

a. Improved Engines: The Panel recommends R&D of the improved engines discussed in the assessment, and suggests the following activities:

(1) Stratified Charge: The exploratory development of this engine has been completed. For the advanced development of this engine, the U.S. Army TACOM has scheduled $3 million in FY 73 and TEP recommends that the advanced development be completed. The additional funding estimated to complete is $10 million.

(2) Lightweight Diesel: There is presently no substantial effort to develop the Lightweight Diesel. The Panel recommends exploratory development, to be followed by advanced development of this engine. Less than $20 million over the next several years is estimated to be needed to complete the effort; however, yearly evaluation and the go/no-go decisions should be based on projected performance, as indicated in Table IV-2.

(3) Gas Turbine: The Panel recommends the development of an advanced gas turbine as outlined in the assessment. EPA is presently supporting a free-turbine development program at about $4.5 million in FY 73 and plans to continue in FY 74 and 75. The Panel supports completion of this activity.

Further, TEP recommends development of a new advanced gas turbine to achieve competitive fuel economy with the other advanced engines, as outlined in the assessment. A few years of exploratory development is recommended and if this stage yields successful results, advanced development should follow. Guidelines for yearly evaluations and go/no-go decisions should be provided by the reference data of Table IV-2. The total funding estimated for completion of advanced development is $30 million.

(4) Rankine: There is a Rankine development program, under EPA sponsorship. The scheduled funding for FY 73 is about $6.5 million and it is planned to continue in FY 74 and 75. The Panel supports the completion of this activity. The funding estimate to complete is $10 million.

In addition TEP recommends advanced development of the next generation Rankine engine to achieve high fuel economy as well as low emissions. Guidelines for yearly evaluations and go/no-go decisions should be provided by the development effort according to the reference data of this report. The estimate to complete this additional development is $30 million.

(5) Stirling: The Panel recommends that exploratory development of the Stirling engine for the passenger car be completed.

(6) Continued Engine Evaluation: Periodic evaluations of the Stirling and other candidate engines for meeting the objectives of a fuel economy engine for automotive application is recommended. Furthermore, an advanced development program for the most promising of these is recommended following completion of appropriate exploratory development. It is estimated that $30 million over several years will be required.

(7) Synthetic Fuel Combustion and Emission Tests: It is recommended that exhaust emission test be funded to obtain a data base for synthetic gasoline and ethanol fuels likely to become economically competitive with gasoline in the future.

b. Supporting Technology and Studies: The Panel recommends a group of additional activities which will contribute substantially to the successful development of automotive propulsion systems with advanced performance for both automobiles and trucks. Included here are: component and transmission development necessary for matching the improved engines to vehicle requirements; review and assessment of advanced concepts in heat engines and hybrids; novel fuel evaluation based on economic studies and experimental results; and studies of vehicle propulsion systems integration. The Panel suggests a steady and continuous activity in this area at a level in the vicinity of 15% of the total effort for the technology.

ELECTRIC PROPULSION TECHNOLOGY

This technology has been assessed to identify alternative technological opportunities for application to ground transportation at lower powers (mainly automobiles and trucks). The need for electrically powered vehicles may arise as a result of severe limitations to the supply of petroleum-based fuels. In such a case, electrical power could be used for ground transportation at large, and is considered a serious alternative.

Electric propulsion for ground transportation is also considered to have additional advantages; it may be more efficient and it will probably be less polluting and less noisy in the long term than conventional propulsion systems. These aspects will be discussed in the following outline of the technology assessment.

1. Assessment Summary.

   There are basically two elements in the technology under consideration: Electric Energy Storage (Batteries), and Electric Power Conversion and Traction (Motor/Control packages). Either the second or both of the aforementioned major elements are necessary in the following applications:

   a. All-Electric, Self-Powered Vehicles: Any vehicle on the road could be such a vehicle, if a long list of serious problems could be resolved. Existing types of batteries do not possess the appropriate combination of energy density, power density, lifetime, and cost to provide electric vehicles with performance capabilities matching those of existing vehicles. Motor/Control packages do exist, but they are inadequate, expensive, and unsuitable for mass production. Electric power production capacity will take many years (say more than 25), before it reaches a point at which it would accommodate the additional load of all-electric ground transportation. The implementation of mass production of electric vehicles and the logistical support (battery charging, maintenance, repairs, etc.) of, say, 10^8 such vehicles are very serious problems. It represents a major deviation from the status quo.

   b. Electric/Electric Hybrid Vehicles: Such vehicles travel partly in a dedicated guideway (with wayside power pick-up), and partly in a free mode using an onboard battery. This battery could be recharged either at arbitrary charging stations or while the vehicle travels in the dedicated guideway. Examples of such vehicles are certain "Dual Mode" designs for future transportation. These vehicles require motor/control packages more sophisticated than the non-constrained electric vehicles, but could operate with less advanced batteries.

   c. Wayside-Powered Electric Vehicles: Such vehicles travel entirely in a dedicated and electrified guideway, like subways do today. Typical examples of such vehicles are the so-called "People Movers" for personalized rapid transit. In these vehicles, a battery is not necessary.

In reviewing these possibilities, the Panel found that items b and c are very useful and worthwhile concepts, but that these concepts are not expected to become sufficiently large consumers of energy to have an appreciable impact. In reaching this conclusion, the Panel considered Table IV-4.[1/] As shown in this table, a total of 3.5 million miles of roads (locals, collectors, and arterials) exist in the U.S. today. This is projected to increase to 4 million miles by 1990, and it includes: urban, small urban, and rural roads. The urban roads only, excluding locals and considering only collectors and arterials, will amount to 188,000 miles. Assuming only two lanes each way, one finds that about 750,000 miles of dedicated guideway must be electrified for a wide range application of concept c, and a substantial fraction of these many miles for a wide range application of concept b. The cost of electrification per mile is known to be between 0.5 and 1 million $/mile. Thus, for electrification (which is not the only expensive item in a dedicated guideway) many hundreds of billions of dollars would be required. Other monumental problems, such as impact on materials, would also arise.

In conclusion, the Panel felt that a wide range application of concepts c and/or b, even for some of the urban roads of the nation, appears logistically unattractive. Limited application in certain urban congested areas might be very attractive, but this would be only a minor perturbation in the Transportation Energy picture. Therefore, the Panel proceeded to assess, in more detail, item a which is the All-Electric, Self-Powered, Vehicle with main emphasis on the passenger auto.

Table IV-5 is informative regarding the current utilization of electric propulsion for ground transportation. Essentially, a small fraction of a percent of the transportation energy is electric (subways and certain commuter rail lines). Furthermore, no more than 0.4% of all motor vehicles are electric today. The currently utilized all-electric self-powered vehicles are about 200,000 Industrial Lift-Trucks and about 200,000 Golf Cars, both rather special applications of All-Electric Transportation.

Current support levels for batteries are summarized below:

	USA Federal & Private ($ Million)	All Other Non-Communist Countries ($ Million)
1. Conventional Batteries (Product Improvement)	1.0 to 1.5	1.0 to 2.0

[1/] See Ref. IV-26

TABLE IV-4. PROJECTED ROAD MILEAGE AND TRAVEL, BY ROAD LOCATION AND FUNCTIONAL CLASS

Functional Class	Location							
	Rural		Small Urban		Urbanized		Total	
	Miles (thou)	DVMT (mill)	Miles (thou)	DVMT (mill)	Miles (thou)	DVMT (mill)	Miles (thou)	DVMT (mill)
Arterials:								
1968	282	822	25	140	70	944	377	1,906
1990	292	1,432	35	233	131	2,247	458	3,912
Collectors:								
1968	691	318	13	20	31	97	735	435
1990	710	420	17	29	57	198	784	647
Locals:								
1968	2,107	189	89	45	262	213	2,458	447
1990	2,105	180	117	50	459	314	2,681	544
Totals:								
1968	3,080	1,329	127	205	363	1,254	3,570	2,788
1990	3,107	2,032	169	312	647	2,759	3,923	5,103

Notes: The definition of arterial, collector and local roads differ depending upon the rural, small urban, and urbanized area categories; therefore, care should be exercised in making comparisons between the corresponding functional classes in different area categories.

DVMT = Daily Vehicle Miles Traveled

TABLE IV-5. DISTRIBUTION OF ENERGY CONSUMPTION IN TRANSPORTATION BY MODE

(1969 Ref. Year)[1/]

Overall Transportation Consumption: 15 x 10^{15} BTU/Year

# Mode		Energy Source	Percent
1 Auto		Oil	51.2
2 Truck	(Intercity Freight)	Oil	9.1
3	(Urban Freight)	Oil	5.1
4	(Service and Utility)	Oil	8.2
5 Bus	(Intercity)	Oil	0.27
6	(Urban and School)	Oil	0.54
7 Rail	(Intercity Passenger)	Oil and Wayside Electric	0.14
	(Freight)	Oil	3.6
	(Subway)	Wayside Electric	0.14
10 Pipeline		Oil and Gas, Mostly	2.0
11 Air	(Passenger)	Oil	11.4
12	(Freight)	Oil	2.6
13 Water	(Passenger)	Oil	0.27
14	(Freight)	Oil	5.8

[1/] See REF. 28.

	USA Federal & Private ($ Million)	All Other Non-Communist Countries ($ Million)
2. High Performance Batteries (Applied Research)	1.5 to 2.5	1.0 to 1.5
3. All Other Batteries (Applied Research & Exploratory Development)	1.5 to 2.0	1.0 to 1.5

As may be seen in the detailed assessment in Technical Appendix I, these support levels are spread over a rather large number of organizations and teams, resulting in subcritical efforts. Current efforts in Electric Power Conversion and Traction (Motors and Controls) are summarized in Table IV-6. As may be seen from this table, the bulk of effort is concentrated in Hardware Development for very specific applications, not related to the all-electric, full performance, passenger auto. Items 4(b) and 6(b) in this Table are for modest R&D activities, aimed at improving the motor/control packages, required for full performance autos.
In addition, NASA is supporting R&D activities (at a level of $0.5 to $1.0M), for Power Conditioning, aimed at Space Applications.

a. <u>Impact of Electric Autos on the Resources</u>: This subject has received a detailed assessment in one of the Sections of Technical Appendix I. The main aspects of this assessment are summarized as follows: in tracing the electric energy from the terminals of a power plant to an electric car on the road the following efficiencies were allocated:

Transmission and Distribution of Electric Energy:	90%
Battery Charging:	80%
Battery Discharging:	80%
Controls:	90%
Traction Motors:	85%

The compound efficiency of all these steps is about 44% (from the terminals of a Generating Power Station to the road power demand of an electric car, including all accessories). Essentially, this figure is a gross average. In actual life, the

TABLE IV-6 SUMMARY OF CURRENT EFFORTS IN ELECTRIC POWER CONVERSION & TRACTION FOR AUTOMOTIVE APPLICATIONS

	ORGANIZATION	ACTIVITY	SUPPORT LEVEL
1.	DOT/FRA &UMTA	Hardware Development for High Speed Ground Vehicles, in the Multithousand HP Range	5 to 10 M $/yr
2.	DOT/UMTA	Hardware Development for Subway Traction	About 1 M $/yr
3.	DOT/UMTA	Hardware Development for People Movers	100 to 300 K $/yr
4.	GE , Westing. , GARRETT , BENDIX , ROHR , FORD , GM .	(a) For Improv. of Existing Products	Few hundred K $/yr per organization
		(b) R & D Oriented Activities	100 to 200 K $/yr per organization
5.	Other little companies & universities	Small Efforts , mainly for Electric Vehicle Promotion , on an Integrated Basis , with State-of-the-Art Hardware.	10 to 100 K $/yr per organization
6.	Western Europe , Britain & Japan	(a) Existing Hardware Improvement	Effort comparable to USA's
		(b) R & D Oriented Activities	Effort, about order of magnitude larger than USA.

tabulated battery discharge efficiency and the motor efficiency are a function of the driving cycle. They are higher for cruising and lower for an Urban Driving Cycle.

With the exception of LWR-Nuclear Power Plants (which have a reference efficiency of 31%), all other Electric Power Plants have a reference efficiency ranging from 35% to 40%.1/ Accordingly, the overall efficiency of electric cars (from the Electric Power Plant Input to Road Demand Power, including all accessories) is between 15% and 18%. This is better than the overall efficiency of typical heat engine cars, using conventional fuels. Calculations in Technical Appendix I show that a typical heat engine car has an efficiency about 14% (from conventional fuel energy to road energy plus accessories). This is for a cruising mode. The corresponding efficiency for an urban driving cycle should be substantially lower.

The electric car overall, with efficiencies of 15% to 18%, could be even more attractive when compared to the efficiency of a typical heat engine car fueled by a "synthetic fuel." If it is assumed that a "synthetic fuel" is derived from primary resources with an efficiency not higher than 70% (consider, for example, methane from coal), then the upper bound would be 14% x (70%) = 10%, for the typical heat engine car, fueled by a "synthetic fuel."

In the absence of more factual data for additional analyses it appears that all-electric autos offer a likely potential of requiring less primary energy resources than is required by the heat engine.

b. Impact of Electric Vehicles on National Power Generation Capacity: Table IV-7 is included to show this relationship. Entry 1 is the reference projected electric energy, in the year indicated.2/ Entries 2, 3, and 4 (for auto, truck and rail, respectively) were obtained by compensating the total projected basic energy demand3/ at the wheels for the power station to wheels efficiency, shown earlier to be 44%. Finally, the power station power required for each mode is referenced to the total power generated (entry 1) to yield the percentages shown in entries 2, 3, and 4. Entry 5 represents the total percentage for all ground transportation.

1/ See page A-32, Ref. IV-28.
2/ See Ref. IV-28.
3/ Ibid.

TABLE IV-7. REFERENCE ELECTRIC POWER PROJECTIONS AND RELATIVE TRANSPORTATION ENERGY PER YEAR

	1969	1977	1985	2000	2020
1. Projected Power Generations 10^9 Kw-Hr/Year	1,553	2,450	3,672	8,000	18,000
2. Auto Power, percent	71%	56%	46%	24%	13%
3. Truck Power, percent	26%	22%	17%	9.5%	4.9%
4. Rail Power, percent	5.1%	4.5%	3.8%	2.9%	2.8%
5. (Auto) + (Truck) + (Rail)	102%	82%	65%	37%	21%

An inspection of the results in Table IV-7 shows that the impact of all-electric ground transportation on electric power generation is not projected to be substantial. This statement is based on the opinion that all-electric ground transportation, even if desirable, could not start being implemented before 1985 to 1990, and it could not be completed before the end of the century. Beyond the year 2000, even fully electric ground transportation would impose an extra demand not exceeding 30% of the projected electric power generation. Such an extra demand could be accommodated in part by an increase of Plant Load Factors (assumed to be 0.55 to 0.65) and in part by a modest expansion of Installed Capacity. Note that many electric batteries could be charged at night.

c. Impact of an All-Electric Transportation on the Environment: (Refer to the data of Table IV-7.) It is pointed out that all-electric transportation does not have a direct impact on the environment. The indirect impact is relatively small by comparison to the impact of the Electric Power Stations, especially beyond the year 2000, when a fully electric ground transportation system may be implemented.

d. Impact of Fully-Electric Ground Transportation on Material Resources: This cannot be determined with any degree of certainty. The main uncertainty here arises from the fact that most components of the electric propulsion hardware are still in the applied research stage and use very appreciable amounts of rare materials such as tantalum, niobium, and tungsten, and novel metals such as platinum, etc. At this stage, if the amounts required per vehicle are multiplied by 10^7 vehicles/year, the resulting amounts are quite large, by comparison to U.S. yearly consumption or even world yearly consumption. Similarly alarming conclusions may be reached if the rare metal amounts, required per electric vehicle, are multiplied by an electric vehicle population of say 10^8 vehicles. The resulting amounts are again large by comparison with U.S. or even global reserves.

However, these alarming conclusions are meaningless in view of the fact that electric vehicles or electric vehicle components would not qualify for mass production, on grounds of excessive costs. One of the most important R&D problems of the all-electric propulsion technology is to design out of the particular components the exotic materials, so that these components may qualify for mass production, if desirable and necessary.

e. R&D Requirements: Generally speaking, there are three separate efforts required to bring about a mass application of a fully electric ground transportation:

(1) Suitable batteries must be developed for full performance vehicles. Such batteries must be able to: store at least 100 watt-hours per pound; provide a power of 100 watts per pound; have a life of, say, 1,000 cycles; and cost about $1/lb.

(2) Suitable Motor/Control packages must be developed. Generally speaking, these packages must weigh less than five pounds per kilowatt. They must be reliable and require less maintenance than today's power drivelines, and they must conform to the general rule "a dollar a pound."

(3) The serious problems of arriving at a production rate of 10^7 electric vehicles per year and of logistically supporting, say, 10^8 electric vehicles on the road must be successfully resolved. These problems are quite serious, in view of the fact that an all-electric ground transportation, in general, is a major deviation from the status quo.

So far, problem (3) is treated on a speculation basis. This is a result of the very slow progress made in items (1) and (2), especially in item (1). The Panel found that the subtechnology of electric motor/control packages is substantially more advanced than the batteries. In the "Electric and Electromechanical Power Conversion and Control for Automotive Applications" workshop of this Panel, detailed consideration was given to the following items: Electronic Components; Control Circuits; Motors; Motor/Control Packages; and Electric System Integration.

A large variety of problems were identified: cost, weight, reliability, demand of strategic materials, etc. Most problems are associated with the control package, but generally all components were found unsuitable for mass production. It was also easily recognized that there is no strong industrial incentive to improve these components, for mass produced autos. Nevertheless, it was estimated that this subtechnology could be brought from the stage of exploratory development (present status) to the stage of preproduction prototype tests (mass production readiness) in 10 to 15 years, at a total cost of $200M. This would include solving all the aforementioned problems of the motor/control package and the integration with the battery, into commercially viable vehicle configurations. It would not include the battery development.

Regarding the batteries, however, the Panel found that substantial applied research and extensive exploratory development would be required before an intelligent decision may be made about advanced development preproduction prototype testing. In other words, the Panel feels that the battery development is the real bottleneck in the engineering development of the all-electric propulsion technology.

For these reasons the Panel feels that batteries should receive priority in development, especially batteries intended for the full performance vehicles. A detailed review of battery R&D status is presented in the Technical Appendix, while a brief outline is presented here. Reference definitions and requirements for batteries appear in Table IV-8, and possible batteries under consideration are tabulated in Table IV-9.

An inspection of these tables shows that full performance requirements may be satisfied either by:

(1) A single battery of the High Temperature Alkali type, e.g., Lithium/Sulfur, Sodium/Sulfur, etc., or by:

(2) A combination of two batteries: One with High Power Density (e.g., Lead/Acid, Nickel/Zinc, Nickel/Hydrogen), and one with High Energy Density (e.g., Fuel Cells, Non Aqueous Alkali, Reduced Temperature Alkali). It is also obvious that most of the aforementioned examples satisfy also the requirements of batteries for intermediate or even limited performance vehicles.

High Temperature Alkali batteries are presently in a state of incomplete applied research. The same is true for High Energy Density batteries. Except for Fuel Cells, which are operational but very expensive, all other concepts require substantial basic and applied research, before an evaluation can be made. High Power Density batteries are substantially more advanced and they are in the state of exploratory development. However, further development of these batteries, without appropriate progress in the development of other batteries, would not be sufficient for full performance electric propulsion.

2. Recommendations.

In view of the presented assessment, the Panel recommends the following strategy for R&D in Electric Propulsion:

TABLE IV-8. REFERENCE DEFINITIONS AND REQUIREMENTS FOR BATTERIES

A. Definitions

	Range (miles)	Max Speed (miles/hr.)	Examples
Limited performance vehicle	50	35	commuter car, buses, delivery vans
Intermediate performance vehicle	100	50	intermediate compact type car, buses, trucks
Full performance vehicle	> 200	80	family type vehicles

B. Energy and Power Requirements

	Limited performance vehicle	Intermediate Performance veh.	Full Performance veh.
Power density (watts/lb.)	40-60	60-90	> 100
Energy density (watt-hrs./lb.)	15-30	30-80	> 100

C. Additional Requirements

Battery Lifetime	> 3 years
Battery Cycle Life	> 50,000 miles
Battery Cost	< 10$/Kw-Hr., capacity

TABLE IV-9. BATTERIES UNDER CONSIDERATION

Vehicle Type	Single Battery Vehicles	Hybrid Vehicles		
		Battery/Battery Hybrids		Heat Eng/Bat Hybrid
		High Power Battery	High Energy Battery	(High Power Battery)
Limited Performance	Pb/PbO_2 Ni/Zn Ni/H_2 metal/air Ni/Fe Zn/Br_2	---	---	---
Intermediate Performance	Ni/H_2 Al/Cl_2 metal/air Sohio cell alkali metal (red. energy) alkaline earth (ambient temp)	Pb/PbO_2 Ni/Zn Ni/H_2 Zn/Br_2	alkali metal (red. power) non-aqueous alkali metal Al/Cl metal/air Sohio cell	---
Full Performance	Li/S Li/Cl_2 Na/S Al/Cl_2 (ambient temp) alkaline earth (ambient)	Ni/H_2 Pb/PbO_2 Ni/Zn Zn/Br_2	alkali metal (red. power) fuel cells non-aqueous metal metal/air	Ni/H_2 Pb/PbO_2 Ni/Zn Zn/Br_2

1/ See Definitions and Requirements in Table IV-8.

a. Step A: Battery Research. A substantial effort is strongly recommended for the completion of applied research and initiation of exploratory development of full performance batteries, especially of the High Temperature Alkali batteries. An appreciable effort is also recommended for applied research in High Energy Density batteries. Non-aqueous alkali batteries (organic electrolyte) and Fuel Cells (catalyst studies), require a relatively low level, long-range, support for applied research. As mentioned earlier, these concepts are being supported presently at subcritical levels which are inadequate for a conclusive evaluation. A suggested funding for this phase is about $10M over the next few years. Most of the effort is suggested for the completion of applied research of the full performance High Temperature Alkali batteries. Yearly evaluation should be based on the reference requirements, outlined in Table IV-8. The same requirements should form the background for a go/no-go decision, at the end of the suggested 3-year schedule.

b. Step B: Battery Development. Promising concepts from a successful completion of Step A are recommended for exploratory development. In this phase, full scale laboratory prototypes should be built and tested according to real life operational cycles. The Panel here estimates and suggests a time scale and funding schedule, approximately $40M over five to eight years. Most of the effort is suggested for the full performance batteries. A steady low level effort is recommended for the High Energy Battery concepts, except if breakthroughs are realized. In this case, the exploratory development effort should be increased for the promising concepts. Again, criteria for yearly evaluation and go/no-go decision should be based on the reference requirements of Table IV-8.

c. Step C: Electric Propulsion Development. Note that Steps A and B are consecutive, and not in parallel. Similarly, Step C should follow a successful completion of Step B, provided that the advanced development of electric propulsion technology is still desirable and necessary. Essentially in Step C the Panel suggests the following activities:

   (1) Advanced Development of Full Performance Single Batteries and/or

   (2) Advanced Development of Full Performance battery combinations (High Energy Battery plus High Power Battery).

(3) Advanced Development of motor/control packages.

(4) Integration of batteries with motor/control packages in electric vehicle prototypes.

(5) Detailed studies regarding mass implementation and logistical support for an all-electric propulsion.

The Panel estimates this phase to require four to five years and about $100M. A comparable effort might be required for the next phase, Step D, which is for complete engineering development of electric vehicles, for initiation of mass production.

In summary, the Panel suggests the following activities:

Battery Research (Appl.):	$10M	3 - 5 years
Battery Development (Expl.):	40M	5 - 8 years
Electric Vehicle Development: (Adv. Development)	100M	4 - 5 years
Electric Propulsion Development: (incl. preproduction prototype)	100M	3 - 4 years
TOTAL	$250M	15 - 20 years

Note that the aforementioned steps are consecutive and not concurrent. Each step is subject to yearly evaluations and go/no-go decision as discussed. Furthermore, each step is subject to a much more fundamental criterion, namely: is the all-electric propulsion necessary and desirable? The Panel feels that a positive answer to this question might be reflected by an accelerated involvement of the private sector.

In any case, the Panel suggests the first step as a near-term R&D activity.

V. TECHNOLOGY OPPORTUNITIES AT HIGHER POWERS

The higher power transportation modes (including air, ship and rail) comprise what is herein referred to as the Heavy Duty Transportation System (HDTS). At present, HDTS accounts for approximately 25 percent of the total transportation energy demand. Its share is conservatively projected to increase to approximately 45 percent by the year 2000 (See Table V-1).

TABLE V-1

THE TRANSPORTATION ENERGY SPLIT[1/]

(Petroleum)

	Percentage of Total				
	1969	1977	1985	2000	2020
Automotive	47	46	40	38	36
Bus	1	1	1	1	2
Truck	23	22	18	17	16
Rail and Subway	4	2	2	3	4
Aircraft	14	24	35	37	35
Ship	6	5	4	4	5
Total Usage, 10^{15} BTU	14.91	21.54	29.97	38.48	48.36

In view of the projected importance of the HDTS relative to overall transportation energy demand, the subpanel for the HDTS assessed a wide variety of technologies which could have a favorable impact on petroleum consumption and fuel diversification for the projected HDTS. Three main approaches were distinguished:

1. Fuel Economy
2. Fuel Diversification
3. Modal Diversification

An assessment summary for each follows:

Technology Assessment

1. Fuel Economy

Table V-2 gives a summary of the possibilities for fuel economy for each of the modes and the potential energy consumption impact by the year 2000.

[1/] See Ref. V-1.

TABLE V-2

Mode	Fuel Consumption Improvement	R&D Cost (1970 Dollars)	Energy Consumption Impact ~ Yr. 2000 (1970 Dollars/Yr.)
Aircraft	25%	300 million	2,000 million
Ship	20%	70 million	70 million
Train	5-10%		70 million

The aircraft offers the best opportunity for getting significant fuel economy increases, principally by vehicle improvements rather than propulsion efficiency improvement per se. NASA estimates that its ongoing Advanced Technology Transport (ATT) R&D Program could achieve 20 to 30 percent improvement in net transportation efficiency (PASS MI or TON MI PER GALLON). The ATT program is investigating across-the-board techniques to reduce aerodynamic drag, obtain savings by auxiliary power-load matching and obtain economy-of-size efficiency improvements in payload to take-off weight ratio for the next generation aircraft. Aerodrag reduction techniques include super-critical wing design, active controls and stability augmentation, all leading to reduced aircraft structure requirements. These will yield 15 to 20 percent improvement. The motorized landing gear, integrated engine generator and dedicated APU technologies are examples leading to 4 to 5 percent energy savings by matching power generator to load requirements. Further economy-of-size efficiency improvement for the larger aircraft will result.

The ATT program total cost is projected at $300 M with technology readiness completed in the early nineteen eighties. The yearly fuel economy benefit is estimated by using 25 percent average reduction of the 89 billion gallons of fuel projected for commercial aircraft consumption in the year 2000. Year 2000 allows adequate time for implementation of the new technology into the aircraft inventory. These assumptions yield an estimated 22 billion gallon fuel saving or a $2.2 billion savings at 10 cents per gallon.

For the ship mode, a 20 percent fuel saving is estimated by incorporating improved engines, primarily closed cycle Brayton or Stirling engines, with multifuel capability and high efficiency. Current ship propulsion is steam turbine (Rankine) at higher powers with a mix of Diesel and steam at the intermediate powers. Typical efficiencies range from 20 to 25 percent for steam and somewhat higher for Diesel. The closed cycle systems should approach 30 to 35 percent system efficiency at design load with very good part-power efficiency as well. In addition, some fuel savings will result from reduced drag on improved ship designs.

An R&D cost of $70 M over several years was projected to develop the heavy duty efficient engines, for both the ship and rail modes. The fuel economy benefit for ships is estimated by assuming 150 new U.S. ships are using the new engines in year 2000[1/]. These ships are assumed in the 40 to 80 thousand SHP class, probably too small for nuclear propulsion, and including some new supertankers. Ships in this class currently use an average of 23 million gallons per year of Diesel fuel oil, thus a 20 percent average efficiency improvement saves 700 million gallons per year or $70 million at 10 cents per gallon.

For the rail mode, the effects of improved fuel economy are expected to result in savings of only 5 to 10 percent. Current rail systems already are highly efficient from an energy view point, using primarily the Diesel engine. Closed cycle Brayton or Stirling engines would help significantly, however, in part-load applications (e.g., in switching yards, etc.). Assuming an 8 percent overall efficiency improvement against the projected rail petroleum consumption in year 2000[2/], a 700 million gallons per year saving results.

2. Fuel Diversification

The panel examined several alternative fuels to kerosene for powering aircraft. These included hydrogen, methane and others. Hydrogen is attractive for long-haul transport because fuel plus tankage gross weight is significantly less for hydrogen than for alternate fuels. The major problem is the increased volume required for storage -- about five times the volume of kerosene. This factor prohibits its use on current aircraft, but a preliminary estimate was made which indicated that an aircraft with a 240,000 lb. payload capability would provide sufficient volume for both payload and fuel. This aircraft would have about 25 to 30 percent lower gross takeoff weight and hence lower thrust requirements when compared to an equivalent JP fueled counterpart.

[1/] See Ref. V-2.

[2/] See Ref. V-1.

The reduced thrust requirement would substantially reduce fuel consumption per unit payload. If Figure V-1 is examined, it is seen that as aircraft size continues to follow historical growth patterns, one might predict aircraft gross weights in the million pounds range by the year 2000. Thus, hydrogen may prove a uniquely advantageous fuel for aircraft. However, hydrogen is expected to cost about 2 1/2 times more per BTU than kerosene does now.

The enabling technology for hydrogen-fueled aircraft would be common to both subsonic and supersonic aircraft. The required effort consists of initial systems studies to define airframe and propulsion requirements and to define technology issues related to fuel system/aircraft integration. It will be important to define the requirements peculiar to the aircraft/terminal interface and cryogenic distribution and handling techniques that might influence aircraft design. The key technology effort would be the development of lightweight and low-cost cryogenic tankage and insulation compatible with vehicle design and integration factors. This effort would place emphasis on support and feed-through design for members. Sample tank designs might be built with vacuum jacket, multifoil insulation alone and combined with solid insulating material. Fabrication techniques, nondestructive test techniques, and thermal performance would be determined. This would also involve materials compatibility, feed-through heat leak assessments, and thermal control of surrounding structure. This effort would provide design specifications. On-board fuel handling techniques, including systems and specifications for pumping fuel between tanks for weight and balance control must be determined and tested. For this effort, safety and hazards evaluations would be done together with tests to provide a basis for safety specifications. These specifications would influence all the technology areas related to aircraft design and operation.

Hydrogen and/or methane may prove feasible for use in ship and rail systems. Ships could be adapted to the use of either with steam propulsion systems. In addition, Diesel engines have already been run with methane at low power, and while it is not considered likely, the rail and ships could use methane in high-power systems, and Diesel engines could be modified for methane.

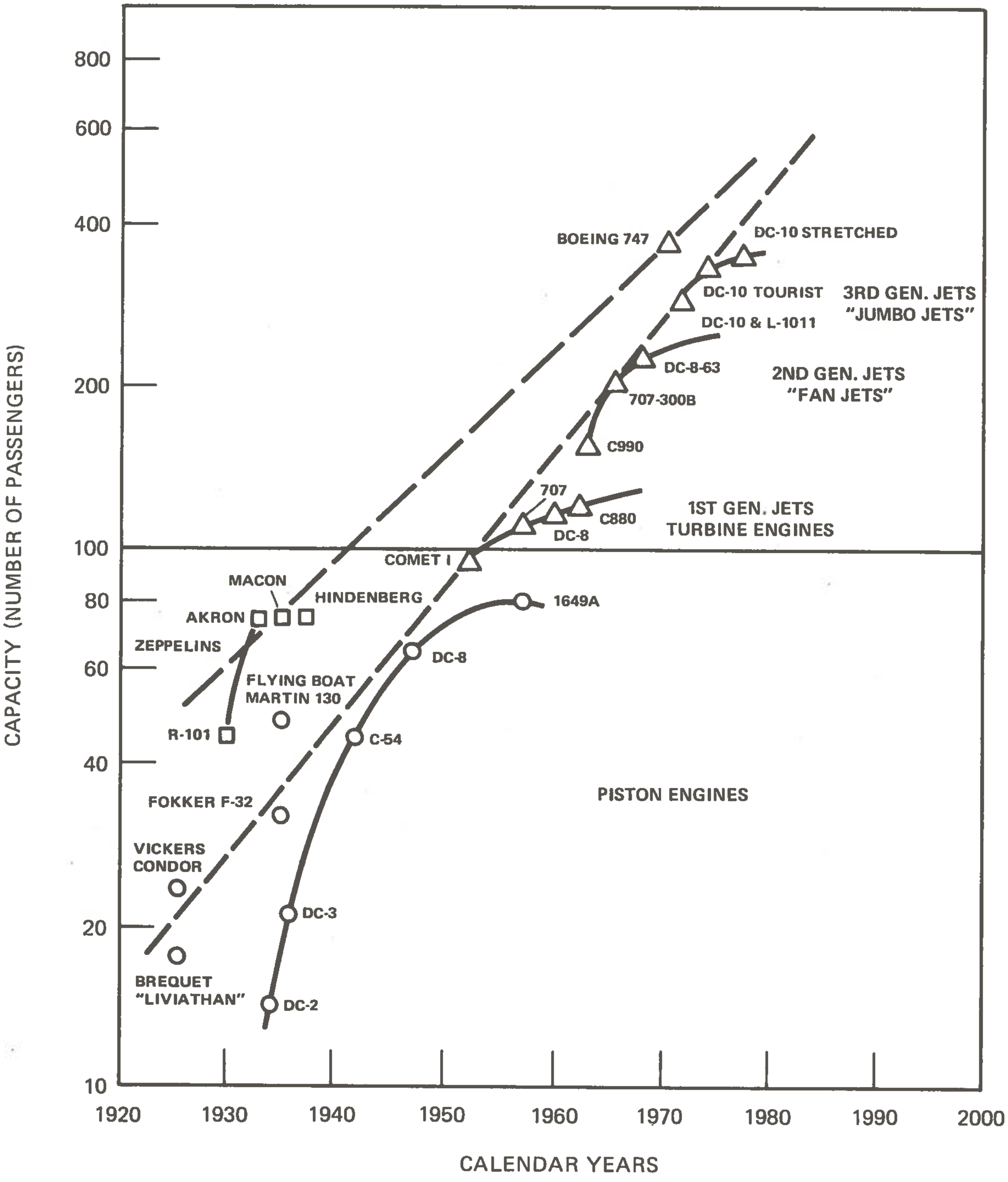


Figure V-1 - Growth in Commercial Aircraft Passenger Capacity

Diversification to nuclear energy is projected soon to be significant for marine transport. Nuclear reactors are already being used as heat sources in naval ships and submarines. A vigorous effort has been initiated by the Maritime Administration aimed at the construction of a fleet of nuclear vessels for the U.S. Merchant Marine. Development of a successful nuclear propulsion system will have several effects, namely:

a. Reduce dependence of the maritime industry on fossil fuel.

b. Present the first step in introducing an alternate fuel to a major transportation mode on an economical scale.

c. Expand nuclear technology and experience in a civilian transportation system.

d. Permit economical operation of high-speed tankers and cargo ships, resulting in a higher frequency of round trips per ship per year.

e. Eliminate payload depletion that occurs with fossil-fueled tankers, which consume a significant portion of the cargo for propulsion and hotel load. This quantity of fuel would become available for domestic use.

Nuclear energy for use in aircraft has also been discussed. A low level effort has been in progress within NASA and USAF for the last seven years. The results, in terms of safety at least, are encouraging, but it is too early to make recommendations regarding the feasibility of nuclear aircraft. As aircraft size continues to increase, however, nuclear aircraft begin to look more feasible from a vehicle design viewpoint.

It is noted that fuel diversification for rail systems does not indicate significant energy savings over the short term. Electrification of rail systems would result in lower petroleum demand, but with central stations converting to natural gas and oil, the drain on petroleum is simply shifted to the power generating sector. Nuclear power generating stations might eliminate the petroleum demand entirely, but projected rail energy demand is still too small to be significantly affected by the type of fuel used.

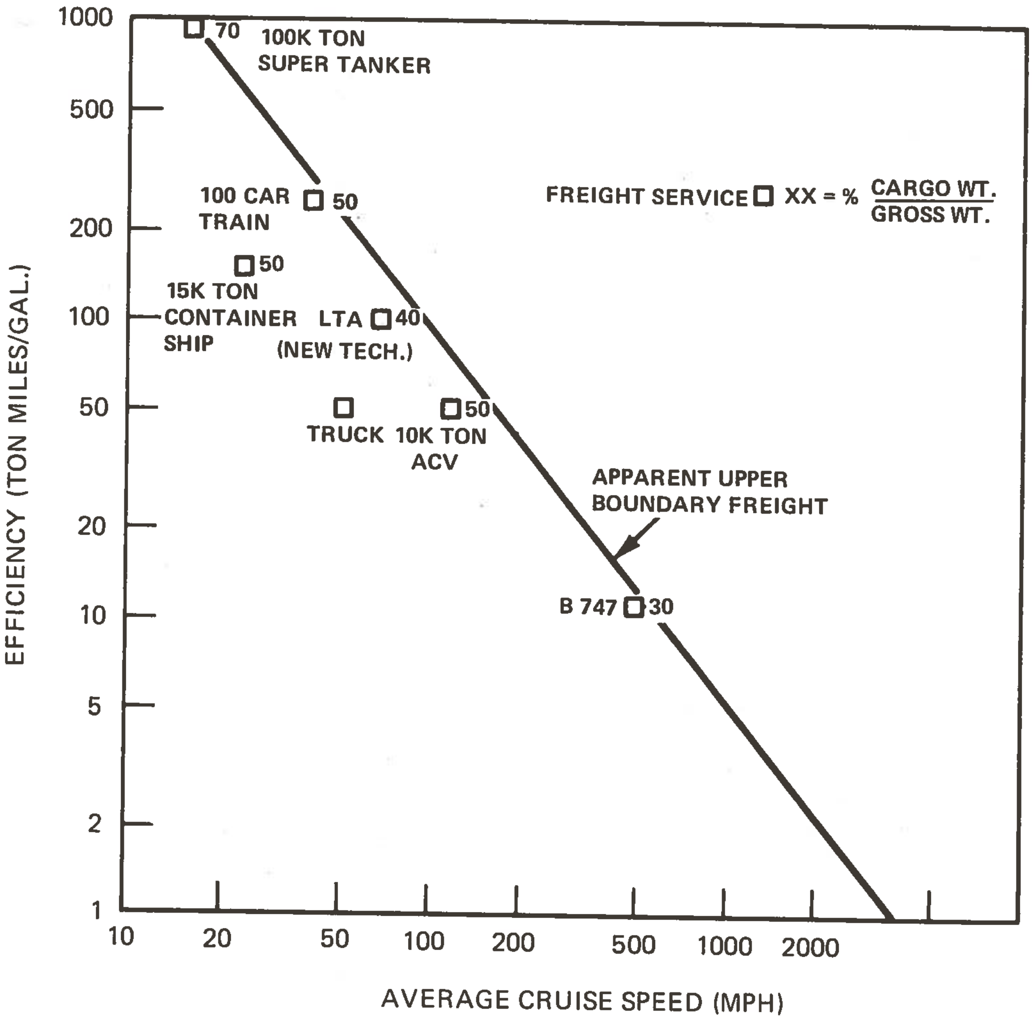
Finally, all of the fuel diversification measures discussed are of necessity long-term solutions. The technology developments needed, the useful life of most heavy duty vehicles, and the historical cycles for introduction of new vehicles all point to the continued need for conventional kerosene-type fuels through the year 2000, at least. Thus, if reduced dependence on petroleum is deemed desirable, then production of synthetic crude oil from shale or coal is essential.

3. Modal Diversification

A possible means of reducing energy demand by HDTS is the development of new vehicle modes. The Panel has investigated several concepts and feels that two of these, the Air Cushion Vehicle (ACV) and the Lighter Than Air Vehicle (LTA) warrant further study.

The ACV will provide a high-speed transport mode at an average of 1/5 the energy per ton-mile of an aircraft with about 3 times the energy consumption of containerized ships. This transportation can be achieved at a cost of approximately 4 to 5 cents/TM. It appears to challenge the truck on both energy consumption and cost but travels faster. The ability of the vehicle to negotiate the land-sea interface means reduced capital investment in terminal (port) facilities and better integration with proposed transportation hubs. The factor of better integrated transport facilities may also reduce energy consumption within the total distribution system. The introduction of such a vehicle could provide the shipper with a new option for otherwise high-value, air-eligible cargo. For example, the ACV, for about 1/5 of the economic cost and 1/5 the energy cost of aircraft would provide about 80 percent of the time savings (that would be provided by jets over ships) on trans-Atlantic trips. Thus, one of the main attractions of the ACV is that it might act as a buffer to the more energy-consumptive air modes.

The LTA, if it were shown to be a viable transportation vehicle, appears to be very energy conservative. The estimated performance shown in Figure V-2 is derived on the basis of $10x10^6$ cubic feet rigid airship in the 650,000 pounds GTOW class. Lift would be provided by helium and the vehicle would utilize boundary layer control for reduced drag and improved low-speed handling performance. It is not proposed to rebuild the "Hindenburg," but rather to investigate an advanced technology design. Its application would best be for long range, overland or water flight.



REF. 3

Figure V-2 - Projected Transportation Energy Efficiency

However, it appears on the basis of new proposals that in-flight cargo transfer may be attractive, making it competitive for short-haul operation. The lack of detailed information and design data makes it impossible to properly assess this vehicle. It has many attributes of the ACV at even lower energy consumption, and the Panel believes it deserves consideration as a future transport option.

Recommendations

1. Support ongoing transportation R&D which is in the interest of petroleum conservation. This includes:
    a. Air Transport Technology (ATT) - the NASA program to develop advanced air transport technology leading to 25 percent decreased fuel consumption with respect to current aircraft.
    b. Nuclear Ship Technology -- the MARAD program to insure an economically viable and competitive ship transportation system essentially decoupled from petroleum resources.
    c. Rail Transport Technology -- the DOT program to enhance the rail mode of transportation to stimulate more public demand for this fuel-conservative mode.
2. Sponsor production development of a nonpetroleum-based, kerosene-like fuel to supplement kerosene in the near future, because modification of the current-generation heavy duty transportation system to use novel fuels is very expensive.
3. Sponsor fuel-diversity technology for light and low cost cryogenic tankage for new air transport fuels and conduct necessary studies to plan for the possible implementation of future hydrogen-fueled air transport.
4. In view of the projected increase in air cargo and the associated increase in energy demand, the panel recommends a study of the practical alternatives to air cargo. The study should include examination of such new modes as lighter-than-air vehicles and large air cushioned vehicles with respect to their potential markets, effects upon surface transport modes, and overall energy impacts. To accomplish this, a "National Transportation Reference System" should be developed similar in function to the "Reference Energy System" developed by the National Energy R&D Goals Study. It should provide information appropriate to assessing the general impact of major modifications to the U.S. transportation system. This includes transportation mode definitions, current and projected modal capacity requirements, cost data, and transportation network information for the major traffic corridors in the United States.

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