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A STUDY OF TECHNOLOGICAL IMPROVEMENTS IN AUTOMOBILE FUEL CONSUMPTION
Volume I: Executive Summary

Donald A. Hurter et al

DECEMBER 1974

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16. Abstract

A study was conducted to determine potential improvements in automobile fuel consumption based on innovative design and components. Standard and compact-size reference vehicles were selected, and a study of how power is used was conducted. Obvious technological innovations (e.g., powerplants (such as spark-ignited, turbocharged, stratified charge, electronic fuel injected, and diesel), transmissions and drive train systems, tires, accessories and auxiliaries, aerodynamics, and weight) that would save on fuel consumption were identified and evaluated, and then screened against program constraints. Operation of reference vehicles equipped with innovative components or redesigned was computer-simulated to predict fuel usage and performance. Techniques to measure fuel economy performance were also developed, and a statistical evaluation of published driving modes was performed. Compliance of innovative components with constraints (such as emissions and safety) and user requirements was determined. Optimized synthesized standard and compact-size vehicles were simulated and total systems evaluation of each vehicle was performed on the basis of fuel usage, performance, technical compatibility, compliance with constraints, user acceptability, and manufacturer adaptability. Synthesized vehicles were ranked in accordance with study objectives, and conclusions and recommendations on designs were drawn. Program plans for synthesized vehicles were also selected.

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PREFACE

This report, prepared by Arthur D. Little, Inc., for the U.S. Department of Transportation, presents a study of technological improvements in automobile fuel consumption. The report consists of three volumes.

Volume I, the Executive Summary, presents a summary of the technical improvements considered and a review of the important conclusions and recommendations. Volume II, the main body of the report, provides a comprehensive discussion of each improvement option, the Government constraints, the synthesized vehicles and the possible fuel economy gains. The appendixes, Volume III, present the original data collected from industry sources, fuel economy and emissions test procedures, and the final letter report from ADL subcontractor, Scientific Energy Systems Corporation.

The status of the technology reported is that available in the time period of July 1973 to January 1974.

Arthur D. Little, Inc., wishes to acknowledge the guidance and assistance provided by Mr. H. Gould, Dr. K. Hergenrother, and Dr. A. Malliaris of the Department of Transportation – Transportation Systems Center; and by Mr. R. Husted of the Department of Transportation, Office of the Assistant Secretary for Systems Development and Technology; and by Dr. K. Hellman and Mr. T. Austin of EPA, Ann Arbor.

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1.0 INTRODUCTION

The almost complete dependency of transportation on petroleum products has been clearly brought into focus by the recent energy crisis caused by the embargo on oil shipments from the Mid-East. The transportation and energy problem has been identified and forecast for some time by government officials, the oil industries, and the automobile manufacturers. Specifically, the President's Office of Science and Technology (no longer existing) addressed this problem. In fact, the Office had been actively examining energy policy matters for about five years. Its members contributed greatly to the President's Energy Message delivered before Congress in June 1971, which focussed wide attention on the overall energy situation.

Further effort was brought to bear on this problem in 1972 with the establishment of a Transportation Energy Panel (TEP). The TEP was an interagency "ad hoc" panel sponsored by the Office of the Secretary, Department of Transportation (DOT). Its participants included the Department of Defense, the Environmental Protection Agency (EPA), the Office of Science and Technology, and the National Aeronautics and Space Administration (NASA). The TEP concentrated its efforts on an assessment of relevant technology which could enhance the use of national energy resources in the transportation sector. The TEP excluded from consideration such areas as improving energy extraction, conversion, transmission and usage by other economic sectors, since these areas were being studied by other panels which had participated in the 1972 energy study.

One result of the TEP's effort was provision of funds for studies such as this one – a Study of Technological Improvements in Automobile Fuel Consumption. The TEP considered the following factors as affecting the requirements for more efficient and more diversified utilization of transportation energy:[1,2]

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, with 55% of the petroleum consumed in the United States used for transportation. This percentage was projected to increase to 60% in the mid-1980's.

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

4. The automobile consumes about 58% of all transportation fuel consumed.

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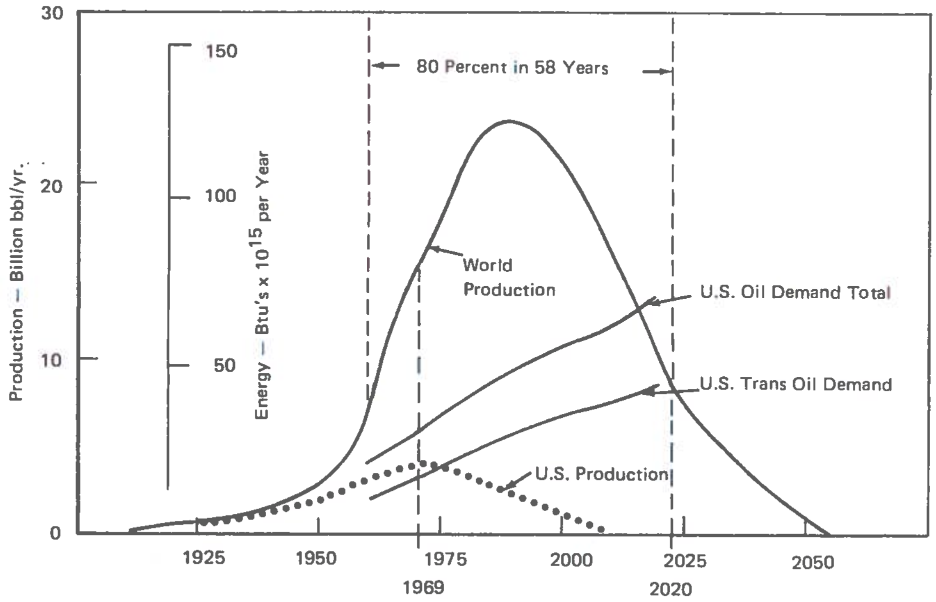
[1] Research and Development Opportunities for Improved Transportation Energy Usage, Report No. DOT-TSC-OST-73-14, Sept. 1972.

[2] Hirst, E., Energy Consumption for Transportation in the United States, ORNL-NSF-EP-15, March 1972.

5. Of the total automobile population in the United States, approximately 90% are family-size cars, that is, six passenger models, averaging approximately 12 to 14 mpg. These figures were revealed by DOT[3] on the basis of total fuel consumption and total vehicle miles in the United States.

6. Based on past projections that did not include the recent oil embargo, which undoubtedly will result in major changes in government energy policies, current projections, made as recently as July 1973,[4] indicate that oil imports could reach approximately 50% by the mid-1970's and increase further to 60% or more by 1980.

7. Finally, although resources other than domestic or imported oil such as shale oil, coal and nuclear energy might be plentiful, an adequate yearly supply to meet transporation needs might be difficult or costly to obtain to offset the petroleum requirement. Figure 1-1 presents the projected world oil production, United States oil production versus the total United States oil demand, and the total United States demand for transportation purposes. These projections are based on trends prior to the oil embargo and without any adjustments for greater efficiency of utilization of transportation and fuel.



Source: DOT-TSC-OST-73-14, Cambridge, Mass., Sept. 1972

FIGURE 1—1 PROJECTED WORLD OIL MARKET AND OIL PRODUCTION

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3. Summary Technical Report of the Transportation Energy R&D Goal Panel, DOT TSC-OST-73-14, September 1972.
4. Energy and the Automobile, SAE Paper SP-383, July 1973.

In addition to the concern generated from the above factors and projections, we feel that the following factors should also have been considered if, in fact, they were not.

1. The federal requirements for emission controls, as applied to present engines, have in part contributed to a marked decrease in the efficiency of the automobile to the point that increases in automobile fuel consumption are estimated to range from 20 to 25%. Coupled with this is a potential 15 to 20% loss in acceleration performance.

2. The automobile manufacturers have also had to comply with federal safety requirements. One result has been an increase in weight which, in turn, has necessitated larger engines causing higher fuel consumption.

The TEP concluded that if the dependency of United States transportation upon oil from foreign sources had to be reduced, there was a large number of possible actions which could be taken – some technological, some institutional, and some involving policy. This conclusion led to the funding, among others, of this project which is concerned primarily with the study of possible technological improvements for highway vehicles which could effect a substantial reduction in fuel consumption. These technological improvements and changes, it was surmised, had the inherent potential of significantly reducing projected energy demand, particularly for petroleum, within the next 15 years.

The Transportation Systems Center of the U.S. Department of Transportation and the U.S. Environmental Protection Agency initiated a program to evaluate the technological feasibility of reducing fuel consumption of the automobile by 30% (43% mpg improvement in fuel economy) or more, based on the reference model of 1973. This goal was predicated on the basis that there would be no significant degradation of performance and that improvements would represent only minimal incremental costs to the consumer. Furthermore, the technological improvements had to be basically available off-the-shelf – at least be in a mature state of development – and capable of being demonstrated in a small number of vehicles by 1976 and mass-producible for automobiles at the rate of 1 million annually by 1980.

Careful consideration of the trend toward smaller cars, which greatly reduces fuel consumption, had been made. However, on the basis that there would continue to be a sustained need for the standard and compact size car by the U.S. public, the study was directed to investigate improvements that could be applied to cars of this size.

Some of the factors leading to the decision to concentrate on standard and compact size cars stemmed from the fact that, at the time, the results of the recent oil embargo had not yet been experienced and there was just no way of measuring the acceptability to the public of the small car concept. Recent increases in fuel costs and the possibility of gasoline rationing have shown dramatically that the buying public will undoubtedly accept and purchase the small car in greater and greater numbers.

The purpose of this study was not to determine how the automobile industry should shift to producing small cars, nor even to determine what would influence the user to buy a small car, but rather to identify and evaluate those improvements which could improve the efficiency of the standard and compact size cars. However, we did recognize in undertaking this study that many of the improvements could be applied to the small car as well with proportional gains to be expected.

2.0 PURPOSE

The primary objective of the work described in this report – a Study of Technological Improvements in Automobile Fuel Consumption – was twofold: (1) to provide some insight into the factors which affect fuel consumption in the passenger automobile, and (2) to identify and evaluate the individual technological improvements which are available in the near term for possible incorporation into a vehicle design which will reduce the fuel consumption (gallons per mile) level of the 1973 passenger automobile by 30%, or improve its fuel economy measured in miles per gallon (mpg) by 43%.

The secondary objective was to provide a source of data for both the Department of Transportation (DOT) and the Environmental Protection Agency (EPA) for use in advising governmental officials on regulatory and policy matters related to minimizing passenger automobile fuel consumption.

3.0 SCOPE AND CONDITIONS OF THE STUDY

3.1 SCOPE

The scope of this six-month (July 73-Jan 74), study involved a number of related tasks which may be briefly described as follows:

Task 1 – Consisted of *selecting reference vehicles* for evaluating the improvements which, when combined, were to yield a 30% improvement in fuel usage (43% improvement in fuel economy in mpg). These vehicles were to be 1973 standard size (3,800 to 4,200 lb) and compact size (2,750 to 3,200 lb) cars. The reference vehicles selected were chosen because they were considered representative of buyer preference of engine size and type, body style, and optional equipment, such as power steering and air conditioning (see Table 3-1).

Task 2 – Consisted of an *examination of the manner in which fuel consumption tests were specified* and run so that data and information could be obtained, compared, and evaluated on a common basis for each improvement. This led to the development of a rationale and a simple model for measuring fuel consumption in which the effect of different driving loads, cycles, and conditions was considered.

Task 3 – Consisted of *compiling well documented experimental data* that could be used to substantiate how the power is used in operating an automobile and also data that could be used to identify and evaluate possible improvements. Since the time scale and funding did not permit accumulating these data by actual testing, we had to develop an approach by which we could obtain these data from automobile manufacturers, component manufacturers, support industries and independent experts, in addition to the developers, and the usual literature and published information.

Because the six-month timeframe for this study did not permit in-depth verification of information provided, wherever possible we made field trips to assess the state of development of the various improvements and to witness their performance tests.

Task 4 – Consisted of *analyzing where power is used in operating an automobile* as a means of determining what areas should receive the greatest priority in identifying and evaluating possible improvements and subsequent fuel savings.

Task 5 – Consisted of utilizing the information and test results obtained *for computer modelling and simulation of fuel economy and performance levels for both size vehicles* – standard and compact – to assess the relative degree of improvement possible for each device, and to provide indications of how the improvements might be combined into a synthesized vehicle design.

Task 6 – Consisted of *further assessment of the improvements against other acceptance criteria outlined* under Section 3.2 – General Conditions (below), if, at this point, they yielded a significant fuel consumption improvement of 3 to 5% or more.

TABLE 3-1

BASE DATA USED TO DEVELOP THE COMPOSITE REFERENCE VEHICLE (1973) FOR COMPACT AND STANDARD PASSENGER VEHICLES

									Range of Parameters For Vehicles Presented	
	Ford		General Motors		Chrysler		American Motors		Composite	
	Compact	Standard	Compact	Standard	Compact	Standard	Compact	Standard	Compact	Standard
Model & Body Style	Maverick 4 Door Sedan	L.T.D. – 2 Door Hardtop	Nova – 4 Door Sedan	Impala – 2 Door Hardtop	Valiant – 4 Door Sedan	Fury – 2 Door Hardtop	Hornet – 4 Door Sedan	Ambassador	4 Door Sedan	2 Door Hardtop
Shipping Weight[3]	2736 lbs.	4100 lbs.	3194 lbs.	4109 lbs.	2865 lbs.	3815 lbs.	2854 lbs.	3774 lbs.	2750-3200 lbs.	3800-4200 lbs.
Curb Weight Including Options (approx.)[1]	2900 lbs.	4292 lbs.	3338 lbs.	4284 lbs.	2965 lbs.	3980 lbs.	3000 lbs.	3900 lbs.	2900-3400 lbs.	3900-4300 lbs.
Wheelbase[1]	109.9"	121"	111"	121.5"	108"	120"	108"	122"	108-111"	120-122"
No. of Cylinders	6	V-8	6	V-8	6	V-8	6	V-8	6	V-8
Engine C.I.D.[1]	250 in.^{3}	400 in.^{3}	250 in.^{3}	350 in.^{3}	225 in.^{3}	360 in.^{3}	232 in.^{3}	360 in.^{3}	225-250 in.^{3}	350-400 in.^{3}
Rated Horsepower[1]	88 @ 3200	168 @ 3800	100 @ 3600	145 @ 4000	105 @ 4000	170 @ 4000	100 @ 3600	195 @ 4400	88-105 HP @ 3200 to 4000 RPM	145-200 HP @ 3800 to 4000 RPM
Standard Axle Ratio[1]	3:00	2:75	3:08	2:73	3:23	3:23	2:73	3:15	3:00 to 3:23	2:73 to 3:23
Standard Tires Belted or Bias[1]	E78-14	G78-15	E78-14B	G78-15	6:95-14	F78-15	6:95-14	F78-14	6:95-14/E78-14	F78-15/G78-15
Air Conditioning[1]										
% Sold with AC	29%	85%	26%	85%	32%	85%	37%	Std.	26%-32%	85%
Price	$363	$410	$381	$405	$358	$391	$377	Std.	$358-381	$391-410
Power Brakes[1]										
% Sold with PB	N.A.	Std.	26%	Std.	9%	Std.	10%	Std.	9%-26%	Std.
Price	–	–	$46	–	$63	Std.	$44	–	$46-63	–
Power Steering[1]										
% Sold with PS	50%	Std.	71%	Std.	70%	Std.	51%	Std.	50%-71%	Std.
Price	$92	–	$100	Std.	$93	Std.	$99	Std.	$92-100	–
Transmission[1]										
% Sold Automatic	86%	Std.	85%	Std.	87%	Std.	83%	Std.	85%-87%	Std.
Price	$177	–	$169	–	$180	–	$200	–	$169-180	–
Approx. Volume Sold 1972	214,000[1]	285,000[1]	368,000[1]	537,000[1]	270,000[2]	280,000[2]	48,000	27,000	214,000-270,000	280,000-537,000
Price	$2566[4]	$4360[5]	$2676[4]	$4174[5]	$2720[4]	$4206[5]	$2642[4]	$4477[5]	$2550-2750	$4175-4360

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1. *Automotive News* data.
2. *Automotive Industries* data.
3. *Red Book* data.
4. Compact-with Power Steering (PS) and automatic transmission.
5. Standard with Air Conditioning (AC), Power Steering (PS), Power Brakes (PB), and automatic transmission.

Task 7 – Consisted of *combining the most promising improvements,* based on automotive engineering judgment, into a complete synthesized design vehicle, and of simulating the fuel economy improvement and performance of the vehicle by means of computer modelling. Certain of the improvements were obviously not additive, and careful consideration was given to the combination of improvements in an individual vehicle, and their benefits to the vehicle were crosschecked by consulting with automotive experts.

Task 8 – *Consisted of a ranking of these designs* – having ascertained what the relative improvements would be for each synthesized design – based on compliance with the general acceptance criteria. A general evolutionary timeframe was then established for each design, and preliminary program plan guidelines were developed for the most promising of the vehicle designs. These were to be used by the DOT and EPA in preparing plans for possible validation tests of the synthesized vehicles.

3.2 GENERAL CONDITIONS OF THE STUDY

Certain study constraints were established as an aid in developing acceptance criteria for the individual improvements and the synthesized designs. They included:

1. Each technical improvement must be in a mature state of development or have reached an off-the-shelf hardware stage, and must contribute significantly to a 30% reduction in fuel consumption (gal/mile) or 43% improvement in mpg when combined into the optimized vehicle design.

2. The synthesized, optimized vehicle must be capable of demonstration by 1976 and be mass-producible by 1980.

3. The performance and transient response of the optimized vehicle design must not be significantly different from the reference vehicle for each of the two sizes – standard and compact.

4. Improvements which resulted in deviations from the federal standard for safety, emissions, and noise should not be incorporated in the vehicle design. It must be pointed out that, to the best of our knowledge, the effects of emission controls have been properly considered. We feel that the improvement concepts included in this study should meet the 1975 federal emission regulation, will probably meet the interim 1976 federal emissions regulations, but will not meet the original 1976 regulations. The emission standards used for this study are the interim 1976 standards which are:

HC	0.41 g/mile
CO	3.4 g/mile
NO_x	2.0 g/mile

Actually we feel that building and testing proposed vehicle models is the only way to validate the overall emission/fuel consumption projections.

5. Factors affecting user acceptability must be carefully considered and differences in them carefully evaluated when compared with the reference vehicle. These factors include:

   a. Cost, including initial cost and operating, repair, and maintenance costs to provide a discounted life cycle cost;

   b. Operating conditions such as comfort, handling, and driveability;

   c. Appearance;

   d. Passenger and luggage capacity; and

   e. Reliability, durability, and ease of maintenance and repair.

4.0 DESCRIPTION OF INDIVIDUAL IMPROVEMENTS AND SYNTHESIZED VEHICLE DESIGNS

4.1 INDIVIDUAL IMPROVEMENTS

The general discussion in this chapter is based on a series of nine tables taken from the main report – *Summary Analysis of the Individual Improvements against the Qualitative and Quantitative Constraints for Both Compact and Standard Size Vehicles* – and these are included at the end of this report. These tables have been designed to permit the reader to compare the innovative devices for the compact and standard size cars against the conditions and constraints of this study. The highlights of the comparison are described below, along with an identification of each of the innovations which were used in each synthesized designed vehicle. The various innovations may be grouped into three major categories as follows:

1) Improved light-weight body and chassis and use of radial tires;
2) Improved engine and transmission matching; and
3) Improved engine systems.

The manner in which these three categories were combined is best shown in Figure 4-1, which also shows the estimated gains for each of the complete systems.

4.1.1 Improved Light-weight Body and Chassis and Use of Radial Tires

Improved fuel economy of approximately 9-13% (8-12% reduction in fuel usage) can be expected from reducing the weight and frontal area by 10%, aerodynamic drag coefficient by 20%, and equipping the vehicle with radial tires. This approach may be applied to any size vehicle with low technical risk, providing the innovations are incorporated in major model changes by 1977-1979. A high level of customer acceptance and cost effectiveness without loss in emission control may be expected as well.

4.1.2 Improved Engine and Transmission Matching

There are two possible approaches – both of which represent substantial cost-effective solutions – which can be used on all size cars and types of engines in this category. The first approach consists of a four-speed automatic transmission with a torque converter equipped with a lock-up device after initial start. This combination makes possible a fuel economy gain of about 13% (11% reduction in fuel usage). Moreover, the estimated initial cost would be approximately $75.00 to the customer, the technical risk low, and implementation could be expected in the 1977-1979 period. Meeting the constraints of this study, including emissions standards, should not present major problems under this approach.

The second approach, based on the use of a continuously variable transmission, presently represents a high technical risk, and is unproven behond the concept stage. Furthermore, the changes required in the design and construction of such an engine to provide durability under

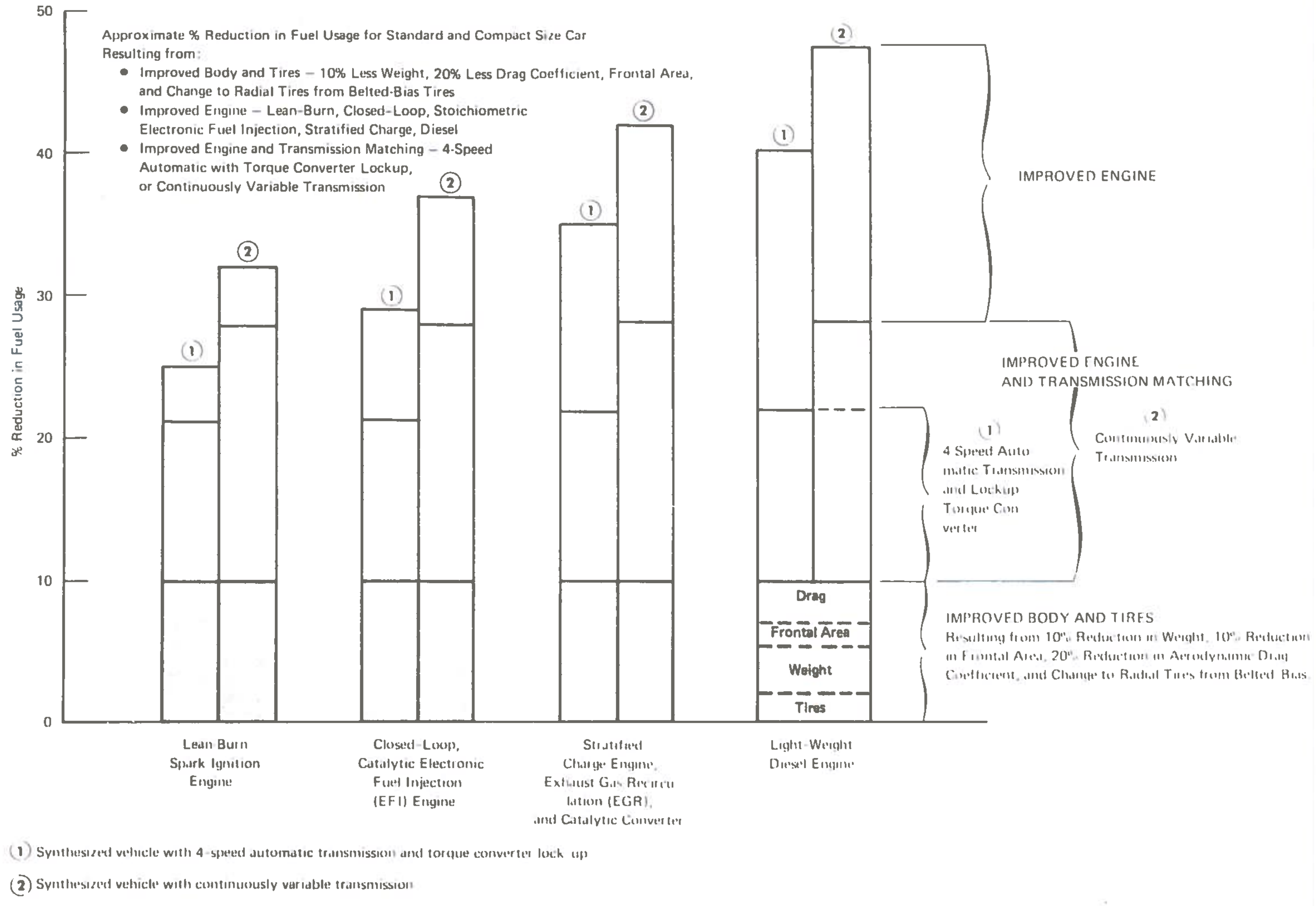

FIGURE 4.1 REDUCTION IN FUEL USAGE FROM PROPOSED IMPROVEMENTS

prolonged optimal loading for best specific fuel consumption operating conditions would require a lengthy engine development period, not to mention a weight penalty as well. Control of NO_x could also present a problem, and the potential noise level produced by the transmission/engine combination looms as another problem. Furthermore, shift logic and a sensor control system would have to be developed. Nonetheless, a fuel economy gain (18% fuel usage reduction) of approximately 23%, providing the technical problems can be solved, appears possible without a substantial loss of approximately 6-12% in transmission efficiency over the engine rpm range from idle (800 rpm) to wide-open throttle (4000-5000 rpm).

We do not foresee this alternative being implementable in production quantities until the early 1980's. However, we have included this concept in the synthesized vehicle because we feel that its potential fuel economy improvement and the concentrated effort being focussed on this type of transmission by the industry indicate that its potential for success on the long term is high. We also feel that the effort to develop the continuously variable transmission could continue in parallel with the development work being expended on the four-speed automatic transmission with torque converter lock-up. If both prove successful – and should the continuously variable transmission offer substantial savings – then it could be offered as an option to the four-speed automatic transmission.

4.1.3 Improved Engine Systems

The potential gains for fuel economy through improved engine systems are predicated on four basic approaches. Two of these are near-term solutions, based on using present spark-ignition engine technology. The third and fourth are based on old concepts requiring extensive engine development and, therefore, are considered long-term solutions. We have summarized the highlights of each of these approaches below.

4.1.3.1 Lean-Burn Engine Concept – Whereas current and past practice in the automotive industry has involved the use of rich air/fuel mixtures to provide good driveability and freedom from manufacturing and maintenance problems, best fuel economy is obtained when the mixture ratio is about 10% lean. As a result, there is a potential 5-20% fuel economy improvement available from lean operation, providing the compression ratio is increased, the ignition system optimized, and a thermal reactor is used.

This improvement is based on the principle that partly loaded (part throttle) internal combustion engines are volumetrically inefficient, and one way of counteracting this effect is to make the air/fuel mixture lean. This tends to force the engine to become more loaded because of less intake air throttling, while at the same time it burns less fuel for each pound of air handled while delivering the required output horsepower.

Our study indicated that the gain in fuel economy attributable to a lean-burn engine would be marginal, amounting to approximately 7.5% (6% fuel usage reduction), and should therefore only be considered a stop-gap measure, until a more efficient engine system can be developed. The technical risks are medium and the chances of success are high, considering that a number of well qualified companies are working on this approach. Each of the approaches being taken by these companies is readily adaptable to the present spark-ignition engine and is not unduly complicated.

At least one developer is considering an electronic fuel injection system which is complicated and costly. However, others are considering modified carburetor systems which have operated satisfactorily. We feel that the concept would be quite cost-effective and durable throughout its life span, with a minimum of maintenance because at present no catalytic converter is considered necessary.

On the negative side, lean air/fuel mixtures cause a problem in driveability or engine response to throttle without hesitation, and, unless this is satisfactorily resolved, the concept could be rejected by the consumer this concept may incorporate the raising of the compression ratio to improve thermal efficiency. This might necessitate the use of high octane fuel. Furthermore, the fuel that is used should be high octane to achieve maximum results by raising the compression ratio of the engine. Since it has not been demonstrated that the interim 1976 standards of 0.41 g/mile of HC can be met, with commensurate improvement in fuel economy, the developers might choose to add a catalytic converter which would augment the vehicle's initial and operating costs.

We expect that the acceptability of the lean-burn concept will be known within the next year as its many developers are reported to be bringing various types of this product into the marketplace. We are predicting that the interim 1975 and 1976 emission standards can be met, but not the original 1976 and 1977 standards.

4.1.3.2 Stoichiometric Air/Fuel Ratio Engines Using Closed-Loop, Self-Tuning Systems and Catalytic Converters – Recently there has been a great deal of effort and interest shown toward the development of systems which result in engines which self-tune for optimal fuel economy, operation, and pollution control. Information provided by the developers indicates fuel economy improvements from 10 to 20% have been obtained during feasibility studies.

The principle behind this approach is that the engine fuel economy, torque output, and exhaust emissions are directly related to the following factors:

- Air/fuel ratio closely controlled at stoichiometric,
- Reduced amount of exhaust gas recirculation,
- Spark timing optimized,
- Spark energy increased,
- Uniformity of mixture.

We indicated in Section 4.1.3.1 that the air/fuel ratio is also extremely important relative to fuel economy, torque output, and exhaust emissions. In the lean burn concept the approach was to operate in the area of leaner than stoichometric, e.g., a 19:1 air/fuel ratio or more, where the three pollutants – HC, CO, and NO_x – could be controlled with exhaust gas recirculation, thermal reactors, and a variety of devices to improve the characteristics of the combustion mixture distribution and ignition.

Closely controlling the approach to operating the engine at slightly richer than stoichiometric is quite different in that recently it has been determined that there is a very narrow pollutant composition window at which the oxidation reactions, which are necessary for the destruction of carbon monoxide and hydrocarbons, and the reduction reactions, which are necessary for the reduction of nitrogen oxide, are essentially balanced. If the compositions of exhaust gases going to a dual-purpose catalyst or so-called three-way catalyst is held with sufficient precision (within about 1 percent) in the vicinity of the optimum zone, catalytic treatment will result in very high simultaneous destruction of all three of the pollutants.

The other important aspect is that the nearly stoichiometric air/fuel ratio necessary for the optimal operation of the catalyst is also the air/fuel ratio which yields the highest torque and close to the lowest specific fuel consumption for a typical eight-cylinder engine of the 400 cubic inch (6.5 liter) class with E.G.R. only. Furthermore, we feel that this approach will permit the return to more optimal spark ignition timing (advance) and less exhaust gas recirculation, used for prevention of NO_X, because the quantities for each of these pollutants are also simultaneously at low level similar to the condition for lean burn.

The principal problem with this approach is the control of the exhaust gas composition within the narrow range through a variety of driving modes and engine and environmental conditions. The key to this close control is a closed-loop feedback mechanism which provides automatic self-tuning. This system depends on a reliable, sensitive, rapid and automatic continuous sensing of the compositon of the exhaust gas leaving the converter. The signal sensed is used to continuously adjust the air/fuel quantities to maintain this optimum composition of exhaust gas entering the converter at all times.

This concept has been included for use in the synthesized design vehicle because it is an extension of the engine systems that will be used for the 1975 model cars which were developed to meet the emission standards. We do not consider this to be a particularly cost-effective approach, however, and question the durability of the system because of yet to be proven results of catalytic converters in a vehicle operated and maintained by the public over a wide range of conditions.

In fact, we see this concept as a relatively short-term solution that will be supplanted by advanced engine concepts as they become available, particularly so if the NO_X level is 2.0 gm/mile. We consider the self-tuning aspects of this system to be quite advantageous, providing a reliable and durable O_2 sensor can be developed and interfaced with a suitable control system for the electronic fuel injection system. The catalytic converter will require replacement during the life of the car – and perhaps sooner – if leaded fuel is inadvertently used in the automobile, or if the condition of the engine is not maintained at proper levels.

4.1.3.3 Stratified Charge Engine – The other approach to the spark-ignited engine is to use a heterogeneous air/fuel mixture, that is, one that is rich at the point of ignition, but becomes progressively leaner through the combustion process – in other words a stratified charge.

The use of air/fuel-charge stratification as a means of improving economy in spark ignition engines has been the subject of experimental endeavor for more than 50 years starting with the early effort of Sir Harry Ricardo. The principal aim of all stratified-charge development has been to operate unthrottled over the complete operating range and vary the load by modulating the fuel supply alone, thus allowing the air/fuel ratio to vary over a wide range. This unthrottled operation eliminates the large pumping loop which gives rise to poor specific fuel consumption at light load in conventional throttled spark ignition engines. To achieve the unthrottled operation it has been necessary to ensure that there is a relatively rich ignitable mixture in the vicinity of the spark plug under all conditions, even though at light load the overall mixture is much leaner.

The principal problem with the stratified charge engine to date has been the flexibility of operation over a wide range of road load conditions. The engines may be made to run very well at steady-state conditions, but are less flexible when a change of load is called for. Therefore, the smoothness of operation and flexibility may not be achievable on all types of stratified charge engines. Offsetting this disadvantage are several advantages, one of which is the ability to use a much broader range of fuels than a gasoline engine. Usable fuels range from gasoline to diesel fuel. Furthermore, the compression ratio of these engines may be increased, depending on the fuel they are programmed to use, thereby providing increased thermal efficiency by virtue of the higher compression ratio.

The stratified charge engine is a 50-year old concept that has yet to be proven for production use in automobiles. Our evaluation does not show this concept to be particularly cost-effective, even though the fuel economy gains are approximately 17.5% (15% fuel usage reduction). The reason is that a complex fuel injection system is required in addition to an emission control system, possibly consisting of catalytic converters. Furthermore, because of the relative complexity of the system, the maintenance and repair costs may be high. We consider this concept to have high technical risk with the major problem to be overcome involving the ability of the engine to be flexible and to operate readily at all speeds and loads.

We have only considered the open chamber-type engine, e.g., those being developed by the Texaco Inc. and the Ford Company, since this is the only concept which affords fuel economy gains. The Honda-CVCC approach has not shown any fuel economy gains over the present 1973 engine, nor has it been fully demonstrated that it can be properly applied to the larger size V-8 engines with reliability and driveability. The success of the subcompact 1973 CVCC Honda introduced in Japan will probably set the pace for full-scale introduction of this concept in the United States. We do not believe this concept will be available before the 1980-1982 period on domestic vehicles.

4.1.3.4 Light-Weight Diesel Engine — Ricardo Consulting Engineers, Ltd., Sussex, England (combustion engine development engineers with extensive experience in automotive diesel engine development) was engaged to make an assessment of the prospects for diesel engines specifically designed for American automobiles corresponding to the compact and standard vehicle sizes investigated herein.

The small, high-speed diesel engine is used in Europe in services where the fuel bill is high and, therefore, any improvement in fuel economy over the alternative gasoline engine shows a significant advantage to the operator. Diesel engines are particularly advantageous in small city and urban delivery vehicles and taxis where operation involves a large proportion of light load and idling modes. It is well known that London taxis fitted with diesel engines use little more than half the fuel consumed by the vehicles with gasoline engines.

In these applications all small diesel engines use indirect or divided chamber combustion systems. This type of chamber more closely approaches the characteristics of the gasoline engine which it replaces in terms of both operating speed range or flexibility and in specific output. The type of direct-injection combustion chamber more normally used in large truck engines, does not lend itself to automobile use, because it has a number of undesirable characteristics such as noise, smoke, and high gaseous emissions apart from its lack of flexibility. Neither is its main attribute of better fuel economy realized in this type of service. The indirect system is known for its low noise and gaseous emissions.

The diesel engine is basically a stratified-charge engine with ignitable mixture occurring at many points in the combustion chamber. Consequently, it is not necessary to throttle the engine at part load to ensure satisfactory ignition and combustion down to very low overall air/fuel ratios. The high compression and therefore expansion ratio adds to the good thermal efficiency. It is at the lighter loads, therefore, where the greatest economies are made. A further area where improvement is achieved in vehicle fuel consumption is under transient conditions where, again, the diesel engine does not require temporary enrichment to avoid marginal ignitability.

Of the four engine improvements considered, we believe that the light-weight diesel offers the greatest potential in fuel economy improvement, amounting to approximately 20% to 25% (16 to 20% fuel usage reduction). We believe that the prechamber-type combustion chamber is most likely to succeed. This concept has apparently overcome the problems of noise and odor. We rate this concept as having a medium technical risk since it is well proven in heavier weight versions. However, an effort must be made to design and develop an engine especially for use in a U.S. automobile rather than to adapt a heavy-duty engine for a light-duty passenger car. This would require a complete engine design and development program, with the chief goal being weight and size reduction commensurate with providing the durability of the present spark ignition engine – that is, 100,000 miles without major overhaul.

This whole concept has to be examined in more depth to prove feasibility in order to allow the widespread changeover to the diesel engine by the 1982/84 period. We see no difficulty in meeting the interim 1976 emission standards.

4.1.3.5 Other Improvements – During the course of this study we also examined other individual improvements, such as –

1. standard engine with catalytic converter and optimized fuel and ignition systems;
2. turbocharged spark ignition engines; and
3. improved accessory drives

Based on our findings, we did not consider these improvements as viable candidates for inclusion into the synthesized vehicle designs. The details and reasons for this conclusion are included in Volume I (Section 4) of the main report.

4.2 SYNTHESIZED VEHICLE DESIGNS

In this section methods used to synthesize various alternative vehicle designs incorporating the individual improvements previously discussed are described for both the standard and compact-size vehicles that will meet the program goals. We evaluated more than one alternative design for each size automobile so that comparisons could be made between individual designs, and so that conclusions as to which have the best chances of success – in terms of fuel savings, cost savings, and compliance with the constraints – could be made. Having evaluated the various vehicle designs, we then ranked them and established a possible evolutionary timetable for introducing the synthesized vehicles.

4.2.1 Vehicle Designs

Table 4-1 lists the various synthesized alternative vehicle designs by type of engine, type of transmission, and size of vehicle. There are four basic engine types generically known as (1) lean burn (LB), (2) closed loop exhaust emission control system, with electronic fuel injection operating at stoichiometric air/fuel ratio (CLEECS), (3) stratified charge (SC), and (4) light-weight diesel (LWD). For each engine we considered two possible transmission improvements, generically identified as (1) four-speed automatic with torque convertor lock-up device, and (2) the continuously variable transmission (CVT). We considered each of the engine and transmission combinations for both the standard size and compact size vehicle, resulting in 16 design concepts – 8 for the standard size and 8 for the compact size.

4.2.2 General Description of Vehicles

The standard-size vehicle weighs between 3800 and 4200 pounds, has a two-door, hardtop body, and is capable of accelerating at a rate equal to the reference vehicle equipped with a 350 to 400 cubic inch, 145- to 200-hp engine operating at 3800 to 4000 rpm. The reference vehicle also includes air conditioning, power brakes, power steering, and automatic transmission.

The compact size car weighs between 2750 and 3200 pounds and is equipped with a six-cylinder, 225 to 250 cubic inch engine rated between 88 to 105 horsepower when operating at 3200 to 4000 rpm. The reference compact car is not equipped with air conditioning or power brakes, but is equipped with power steering and automatic transmission. In all cases the standard and compact synthesized vehicle designs performed – that is accelerated – within 10% of the acceleration norm of the reference vehicle.

TABLE 4–1

LIST OF 16 LIGHT–WEIGHT SYNTHESIZED VEHICLE DESIGNS EVALUATED

Engine Concept Type	Transmission Type Matched to Engine	Standard Size Vehicle	Compact Size Vehicle	Total Vehicles
Lean Burn (L.B.)	● 4 Speed Automatic with Torque Converter Lock-up (4 S.A.T.C.L.U.)	X	X	2
	or			
	● Continuously Variable Transmission (C.V.T.)	X	X	2
Closed Looped Exhaust Emission Control System (C.L.E.E.C.S.)	● 4 S.A.T.C.L.U.	X	X	2
	or			
	● C.V.T.	X	X	2
Stratified Charge (S.G.)	● 4 S.A.T.C.L.U.	X	X	2
	or			
	● C.V.T.	X	X	2
Lightweight Diesel (L.W.D.)	● 4 S.A.T.C.L.U.	X	X	2
	or			
	● C.V.T.	X	X	2
4 Engines	2 Transmissions for Each Engine Type	8 Systems	8 Systems	16

Note: All vehicle designs based on using radial tires 10% reduction in weight, frontal area and 20% reduction in aerodynamic drag.

4.2.3 Innovative Improvements Common to All Vehicle Designs

There were certain innovative improvements which could be applied to all vehicles, either separately or in combination. For this study each of the 16 designs included incorporation of the following improvements:

1. 10% reduction in vehicle weight,
2. 10% reduction in frontal area,
3. 20% reduction in aerodynamic drag coefficient and
4. substitution of radial tires for conventional belted bias tires.

The individual contribution to fuel economy improvement for each of these approaches is discussed in detail in Section 4 of the main report.

4.2.4 Engine and Transmission Improvement

We next examined each engine improvement type on an individual basis without consideration of optimizing that engine's performance by proper matching to an improved transmission; conversely each transmission improvement was examined only in terms of how it would improve the performance of a standard spark ignition engine, but not in terms of how it would affect an improved engine, such as a stratified charge or a diesel. We then combined each of the improved engine types with either the four-speed automatic torque converter with lockup or a continuous variable transmission and predicted the anticipated improvement that this combination would effect for each of the engine designs.

To the best of our knowledge combining the various improved engines with the two different types of transmission improvements has not been demonstrated in actual experimental tests. Therefore, our projections are based purely on simulation and are subject to validation when the various improvements become available. Furthermore, since they are simulations, we can only offer opinions as to whether these combinations would comply with the constraints of the study.

4.3 SIMULATION OF VARIOUS SYNTHESIZED VEHICLES

Our approach in determining the improvement in fuel economy or percentage reduction in fuel usage was based, where possible, on actual experimental data (i.e., data furnished by the innovators) to simulate the vehicle operation on a computer. However, when simulating fuel economy for a synthesized vehicle design, combinations of different devices were tried simultaneously so that the proper interaction of these innovations, as a total system, could be measured. This was particularly important when matching the transmission to an engine for various road load conditions.

Furthermore, we gave attention to adjusting engine size, so that the acceleration of the synthesized vehicle fell within 10% of the comparable reference vehicle's acceleration. If this were not done, then comparisons in fuel economy gains – or fuel usage reduction – would be erroneous. Having determined the miles per gallon for each of the different driving conditions – viz., the

Federal Driving Cycle and steady-state conditions – 30, 40, 50, 60, and 70 miles per hour – we took the same approach to determine the total yearly tank mileage or fuel used in 10,000 miles. We then determined the total usage for three years, or 50,000 miles, which we felt represented the period of time the first owner would keep the car before trade-in and, secondly, for 100,000 miles of use, or 10 years, which represented the normal life of an automobile.

4.4 SUMMARY OF RESULTS AND COSTS

4.4.1 Fuel Economy Gains and Costs

Tables 4-2 and 4-3 consist of three lines of demarcation, as shown by the three horizontal sections. Section 1 relates to initial increment costs for each design over the sticker price for the reference vehicle. These costs are our best estimates, and are based on our discussions with both developers and representatives of the automotive industry.

Section 2 lines show the fuel economy improvement and gallons saved over a 3-year (50,000 mile) period and 10-year (100,000 mile) period. The driving cycle and tank mileage calculations used for Section 2 were developed for this study and are described in Section 4 of the main report. The method and data provided will allow the reader to modify these values to suit his own driving cycle if he so desires.

Section 3 is a measure of cost effectiveness, that is, a yardstick used to measure the overall monetary benefit of an improved vehicle design, i.e., benefits (savings) over the life cycle of the vehicle (3 and 10 years). To be considered cost-effective, these benefits should exceed the overall cost (section 1) of fuel for the same period.

As stated before, the automobile manufacturers are well aware of the advantages and disadvantages of each of these systems and are, in fact, developing or re-examining previous developments to determine if, in their opinion, one or more has become a cost-effective solution in light of the increased cost for fuel.

Tables 4-2 and 4-3 display the fuel economy gains or commensurate fuel usage reduction over the reference vehicle for each of the synthesized designs and the gallons of gasoline saved for the 3- and 10-year periods. The table shows that many of the synthesized vehicle designs exceeded the goals of this study. The fuel usage reduction ranged from 20% for the lean-burn, four-speed automatic with torque converter lock-up standard size vehicle to 46% for the diesel- and continuously variable transmission-equipped standard size car. The fuel usage reduction ranged from a minimum of 25% for the lean-burn, four-speed automatic with torque lockup compact size car to 47% for the light-weight diesel and continuously variable transmission-equipped compact car.

Tables 4-2 and 4-3 also show the gallons saved for 3 and 10 years for each of the designs. It is significant to note that the amount of gas saved, depending upon the design concept, ranged from 130 gallons to 250 gallons in 10,000 miles for the compact size car and 138 gallons to 316 gallons in 10,000 miles for the standard sized car. The tables also show the total estimated incremental cost

TABLE 4–2

COMPACT SIZE VEHICLE
SUMMARY OF INVESTMENT COST DATA FOR SYNTHESIZED DESIGNS OF VARIOUS ENGINE TRANSMISSION CONCEPTS MEASURED AGAINST A RANGE OF FUEL COSTS

		Lean Burn				Closed Loop Exhaust Emission Control System				Stratified Charge				Diesel			
		4-Sp + Auto + Lock-up		C.V.T.		4-Sp + Auto + Lock-up		C.V.T.		4-Sp + Auto + Lock-up		C.V.T.		4-Sp + Auto + Lock-up		C.V.T.	
Section	**Definition of Cost**	1st Owner	10 yrs	1st Owner	10 yrs	1st Owner	10 yrs	1st Owner	10 yrs	1st Owner	10 yrs	1st Owner	10 yrs	1st Owner	10 yrs	1st Owner	10 yrs
	Initial Incremental ^ Cost $	305	305	390	390	505	505	590	590	605	605	690	690	705	705	790	790
	Total △ Repair & Maint. Cost $	30	100	30	100	90	300	90	300	90	300	90	300	–	–	–	–
1	Total △ Replacement Cost $	-80	-40	-80	-40	-80	+60	-80	+60	-80	-40	-80	-40	-80	-40	-80	-40
	Total △ Cost $	255	365	340	450	515	860	600	950	615	865	700	950	625	665	710	750
	Fuel Economy Improvement %	31	31	41	41	35	35	45	45	42	42	52	52	50	50	60	60
2	% Fuel Usage Reduction (FUR %)	25	25	32	32	29	29	37	37	35	35	42	42	40	40	47	47
	Gallons Saved (Tank Mile # x %FUR)	651	1302	833	1666	755	1510	963	1926	911	1822	1094	2188	1042	2084	1224	2448
	Dollars Saved @ $0.40/gal	260	520	333	666	302	604	385	770	364	728	438	876	416	832	490	980
	Net Saving @ $0.40/gal	5	155	-7	216	-213	-256	-215	-180	-251	-137	-262	-74	-209	167	-220	230
	Dollars Saved @ $0.50/gal	326	652	417	834	377	755	501	1002	466	912	547	1094	521	1042	612	1224
	Net Saving @ $0.50/gal	71	287	77	384	-138	-105	-99	+52	-149	+47	-153	144	-104	377	-98	474
	Dollars Saved @ $0.75/gal	488	976	625	1250	566	1132	722	1444	683	1366	820	1640	782	1564	918	1836
3	Net Saving @ $0.75/gal	283	611	285	800	51	+272	122	494	68	501	120	690	157	899	208	1086
	Dollars Saved @ $1.00/gal	651	1302	833	1666	755	1510	963	1926	911	1822	1044	2188	1042	2084	1224	2448
	Net Saving @ $1.00/gal	396	937	493	1216	240	650	363	976	296	957	394	1238	417	1419	514	1698
	Dollars Saved @ $1.25/gal	814	1628	1042	2082	944	1888	1203	2406	1138	2276	1368	2736	1302	2604	1530	3060
	Net Savings @ $1.25/gal	559	1263	702	1632	429	1028	603	1456	523	1411	668	1786	677	1939	820	2310
	Fuel Cost per Gallon to Breakeven Based on Total △ Cost	.39	.28	.41	.27	.68	.56	.62	.49	.67	.47	.64	.43	.59	.32	.58	.31

*FUR = Fuel Use Reduction

Assumptions:

1. Compact size reference vehicle
2. Tank mileage = 19.20 mpg for the standard size reference vehicle
3. Three years = 50,000 miles = 2604 gals. gasoline used
4. 10 years = 100,000 miles = 5208 gals. gasoline used
5. Heavy horizontal black line indicates breakeven point between investment and fuel cost/gallon based on 1–3 above
6. ^ = difference between the reference vehicle and proposed engine transmission concept
7. Net savings = total ^ cost – dollars saved at a fuel cost

Note:
0% ———
6% – – – – –
10% — — —
18% –·–·–·–

These lines define the gasoline price which satisfies the present value of future savings and cost criteria at different % discount rates.

TABLE 4–3

STANDARD SIZE VEHICLE
SUMMARY OF INVESTMENT COST DATA FOR SYNTHESIZED DESIGNS OF VARIOUS ENGINE TRANSMISSION CONCEPTS MEASURED AGAINST A RANGE OF FUEL COSTS

		Lean Burn				Closed Loop Exhaust Emission Control System				Stratified Charge				Diesel			
		4-sp-Auto + Lock-up		C.V.T.		4-sp-Auto + Lock-up		C.V.T.		4-sp-Auto + Lock-up		C.V.T.		4-sp-Auto + Lock-up		C.V.T.	
Section	**Definition of Costs**	1st Owner	10 yrs	1st Owner	10 yrs	1st Owner	10 yrs	1st Owner	10 yrs	1st Owner	10 yrs	1st Owner	10 yrs	1st Owner	10 yrs	1st Owner	10 yrs
1	Initial Incremental Δ Cost $	330	330	430	430	570	570	695	695	770	770	870	870	870	870	970	970
	Total Δ Repair & Maint. Cost $	30	100	30	100	90	300	90	300	90	300	90	300	–	–	–	–
	Total Δ Replacement Cost $	-100	-60	-100	-60	-100	+40	-100	40	-100	-60	-100	-60	-100	-60	-100	-60
	Total Δ Cost $	260	370	360	470	560	910	685	1035	760	1010	860	1110	770	810	870	910
2	Fuel Economy Improvement %	24	24	34	34	29	29	39	39	36	36	51	51	44	44	60	60
	% Fuel Use Reduction (FUR%)	20	20	28	28	26	26	34	34	30	30	39	39	36	36	46	46
	Gallons Saved (Tank Mile # x %FUR*)	688	1376	963	1926	895	1790	1169	2338	1032	2064	1341	2682	1238	2476	1582	3164
3	Dollars Saved @ $0.40/gal	275	550	385	770	358	716	468	936	413	826	536	1072	495	990	633	1266
	Net Savings @ $0.40/gal	15	180	25	300	-202	-194	-217	-99	-347	-184	-324	-38	-275	+180	-237	356
	Dollars Saved @ $0.50/gal	344	688	482	964	498	896	584	1168	515	1030	670	1341	619	1238	791	1582
	Net Savings @ $0.50/gal	84	318	122	494	-112	-14	-101	133	-245	20	-190	231	-151	428	79	672
	Dollars Saved @ $0.75/gal	516	1032	772	1444	671	1342	876	1752	774	1548	1005	2110	928	1856	1186	2372
	Net Savings @ $0.75/gal	256	662	412	974	111	432	191	717	14	538	145	1000	158	1046	316	1462
	Dollars Saved @ $1.00/gal	688	1376	963	1926	895	1790	1169	2338	1032	2064	1341	2682	1238	2476	1582	3164
	Net Savings @ $1.00/gal	428	1006	603	1456	335	880	484	1303	272	1054	481	1572	468	1666	712	2254
	Dollars Saved @ $1.25/gal	860	1720	1203	2406	1119	2238	1462	2922	1290	2580	1676	3352	1547	3094	1978	3956
	Net Savings @ $1.25/gal	600	1350	843	1936	559	1328	777	2819	530	1570	816	2242	770	3013	1108	3046
	Fuel Cost per Gallon to Breakeven Based on Total Δ Cost	$.38	.27	.37	.24	.63	.51	.58	.44	.74	.49	.64	.41	.62	.33	.55	.29

*FUR = Fuel Use Reduction

Assumptions:

1. Standard size reference vehicle
2. Tank mileage = 14.54 mpg
3. Three years = 50,000 miles = 3440 gals. gasoline used
4. 10 years = 100,000 miles = 6880 gals. gasoline used
5. Heavy horizontal black line indicates breakeven point between investment and fuel cost/gallon based on 1-3 above
6. Δ = difference between the reference vehicle and proposed engine transmission concept
7. Net savings = total Δ cost – dollars saved at a fuel cost

Note:		
0%	———————	These lines define the gasoline price which satisfies the present value of future savings and cost criteria at different % discount rates.
6%	- - - - - - - -	
10%	—— —— ——	
18%	–·–·–·–·–	

over the reference vehicle cost for each of the concepts. This incremental cost figure was used to measure the cost effectiveness of each design by comparing it to the gallons saved and multiplying by the fuel cost per gallon for the time period being examined.

Discount factors 0, 6, 10, and 18 percent were applied and the breakeven cost per gallon was indicated by the various percentage lines shown on each of the charts. At the bottom of the chart the breakeven fuel cost per gallons, based on the total incremental cost, is shown at a zero discount rate. Generally the fuel cost per gallon breakeven point for the synthesized vehicles was lower than the fuel cost breakeven point for the individual improvements, particularly the individual engine types. The reason for this is that the synthesized vehicles have incorporated the relatively low incremental cost of the light-weight body and chassis improvements, as well as the transmission improvement, which has offset the relatively high cost of the engine types employed. Therefore, in performing the total evaluation of a synthesized vehicle, care must be taken to account for this factor properly.

4.4.2 Summary of Highlights Concerning Fuel Economy Gains and Costs for Synthesized Vehicle Designs

The following is a list of highlights that may be obtained by reviewing Table 4-2 and Table 4-3.

- *The lean-burn concept* results in the lowest total incremental cost to the first owner and for the life cycle of the vehicle for both the compact and standard size car. Secondly, it is the most cost-effective solution either with a four-speed automatic transmission with lockup or a continuously variable transmission. This concept becomes cost-effective when the fuel cost reaches approximately $0.24 to $0.41 per gallon for both size automobiles.

- *The closed-loop exhaust emission control system,* either with four-speed automatic transmission and lock-up or continuously variable transmission, has a very high total incremental cost for either the 3- or 10-year period. It has a fuel cost per gallon breakeven point almost double that of the lean-burn concept ranging from $0.68 (3 years) to $0.59 (10 years) a gallon for the compact sized car and $0.63 (3 years) to $0.44 (10 years) a gallon for the standard size car.

- *The stratified charge engine concept,* either with the four-speed transmission or the continuously variable transmission, has the highest total incremental cost over the reference vehicles of all four concepts and, therefore, requires a fuel cost per gallon to break even of $0.63 (3 years) to $0.43 (10 years) for the compact car and $0.74 (3 years) to $0.41 (10 years) for the standard size car.

- *While the light-weight diesel* has a relatively high incremental total cost, it begins to approach the cost effectiveness of the lean-burn concept for the 10-year, 100,000-mile life cycle time period. The breakeven fuel cost under these conditions is \$0.33 per gallon for the four-speed transmission design and \$0.29 per gallon for the continuously variable transmission design. For the 3-year period, the cost effectiveness is not so attractive, resulting in a fuel cost per gallon ranging from \$0.62 per gallon to \$0.55 per gallon, depending upon the transmission type.

- Thus, one can conclude that the lean-burn concept would be the most cost-effective system to develop for the 1977 to 1980 period, and for the 1980 to 1985 period the light-weight diesel would be the most cost-effective design. Finally the closed-loop exhaust emission control system and the stratified charge systems would be the least attractive to develop.

4.5 SYSTEM COMPARISON BETWEEN SYNTHESIZED VEHICLE DESIGNS

Table 4-4 summarizes the potential improvements of both the compact and standard size vehicles, as described in Section 4.2.1 and Table 4-1. This table was compiled primarily to highlight the salient features of each synthesized design so that they could be compared one against the other. The table provides the reader with the major advantages and disadvantages of each system. The highlights of this table follow:

1. The lean-burn engine concept with four-speed, automatic, torque converter, lockup transmission and improved light-weight vehicle with radial tires provides a near-term, potentially low-risk solution for reducing fuel consumption by 20-25%, depending on the size of automobile. Many capable companies are working on this concept which can be readily adapted to present-type engines if the solutions prove feasible. As stated before, we believe this concept – with a modified carburetor and thermal reactor – probably has the greatest chance for success in the most cost-effective manner. However, the area of concern with this concept is driveability, because of the cylinder-to-cylinder and cycle-to-cycle variation in the combustion process. Furthermore, while we feel the interim 1975 and 1976 emission standards will probably be met, validation tests will be required. We foresee this concept being implemented for either size vehicle in the 1977-1981 period.

2. The companion to concept No. 1 is the same light-weight vehicle with lean-burn engine, but equipped with a continuously variable transmission. As can be seen, the fuel usage reduction percentage is increased to 28-32%. However, the risk is higher for this concept because of the unproven aspect of the continuously variable transmission. In addition, the engine itself may have to go through a development phase, so that its potential lack of durability, because of the continuously high loads imposed by the proper matching of the transmission to the engine, can be overcome. Furthermore, the loaded engine may present problems with NO_x which would have to be validated by test.

   Both of the lean-burn designs discussed above, in our opinion, will not require catalytic converters when fully developed, but will require a higher octane fuel than is presently being contemplated for the future. We recognize that this concept, as

TABLE 4-4

SUMMARY OF POTENTIAL IMPROVED COMPACT AND STANDARD SIZE VEHICLES*

VEHICLE CONCEPT	STANDARD SIZE							REMARKS	COMPACT SIZE			
	% FUEL ECONOMY IMPROVEMENT	% FUEL USAGE REDUCTION	ESTIMATED FUEL SAVED IN 10 YEARS AND 100,000 MILES	ESTIMATED NET SAVINGS BASED ON 10 YEARS @ $0.75/GAL	RISK	TIME FRAME	COMPLIANCE WITH CONSTRAINTS		% FUEL ECONOMY IMPROVEMENT	% FUEL USAGE REDUCTION	ESTIMATED FUEL SAVED IN 10 YEARS, 100,000 MILES	ESTIMATED NET SAVINGS BASED ON 10 YEARS @ $0.75/GAL
1. Light-Weight Vehicle with Radial Tires, Lean-Burn Engine, and Thermal Reactor, and Either: 4-Speed Automatic and Torque Converter Lockup Transmission	24	20	1376	662	Low	1978-1981	*	● Many Lean-Burn Concepts Being Developed ● Readily Adaptable to Present Engines ● Driveability may be a Problem Due to Cylinder-to-Cylinder and Cycle-to-Cycle Variation ● Combination of New Engine and C.V.T. Presents High Risk ● Does not Require Catalyst, but may Require High Octane Fuel or Leaded Fuel For Best Economy	31	25	1302	611
or Continuously Variable Transmission	34	28	1926	974	High	1981-1984	* Loaded Engine may present problem with NO_x		41	32	1666	800
2. Light-Weight Vehicle with Radial Tires, Engine Equipped with Closed-Loop Stoichiometric Fuel Control and Catalytic Emission Control					Low	1975-1977	* Emission Control Dependent on Keeping in Tune and Life and Reliability of Catalyst	● Start Development Based on Proposed 1975 Engines with Optimized Spark Timing, Improved Carburetor, and Catalytic Converters; Improve with Closed-Loop if System is Successful ● Catalytic Muffler Unproven in Public Hands ● Uses Noble Metals which must be Imported ● Catalyst must be Replaced at 50,000 Miles				
4-Speed Automatic and Torque Converter Lockup Transmission	29	26	1790	432	Medium	1981-1984			35	29	1510	272
or Continuously Variable Transmission	39	34	2338	717	High	1981-1984			45	37	1926	492
3. Light-Weight Vehicle with Radial Tires and Stratified Charge Engine 4-Speed Automatic and Torque Converter Lockup	36	30	2084	538	High	1982-1984	* Good Results to Date	● Engine must be Developed into Reliable Power Plant ● Requires Both Fuel Injection System and Spark Ignition System ● Maintenance Cost Probably High ● Concept Being Explored Extensively and Answers Should be Available in Near Term ● Highest Risk of All Concepts ● Uncertain Cost Effectiveness	42	35	1822	501
or Continuously Variable Transmission	51	39	2682	1000	Very High	1982-1984			52	42	2188	690
4. Light Weight Vehicle with Radial Tires and Diesel Engine 4-Speed Automatic Transmission and Torque Converter Lockup	44	36	2476	1046	Medium	1982-1984	*NO_x May Present Problem	● Good Cost-Effective Solution ● Technical Risks, Medium to High Development Required on Odor, Cold Start, and Weight ● Should be Reliable with Low Maintenance ● Changeover to Large-Scale Diesel, Fuel Production must be Studied	50	40	2084	899
or Continuously Variable Transmission	60	46	3164	1462	High	1982-1984			60	47	2448	1086

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* Figures in this chart, to the best of our knowledge, include the effects of emission controls. We feel that the improvement concepts included in this table should meet the 1975 federal emission regulations, will probably meet the interim 1976 federal emission regulations, but will not meet the original 1976 regulations. Actually, we feel that building and testing the proposed vehicle models is the only way to validate the overall emission/fuel consumption outputs.

All Vehicles must be Engineered to Meet Safety Requirements.

yet, has not reached a point where both emission standards and commensurate fuel economy have been fully demonstrated, and if the developers choose to introduce a catalytic converter into the system for added flexibility to recalibrate the vehicle for emissions, there will be an increase in initial and operating cost and only non-leaded, high octane fuel will be usable.

3. We see the next design concept – the light-weight vehicle with radial tires equipped with an engine having closed-loop stoichiometric fuel control and catalytic converter emission control and a four-speed automatic transmission with torque converter lockup – developing from standard engines that will be offered on the 1975 production vehicles. These vehicles will be equipped with optimized spark-timing, improved carburetion, and catalytic converters. Time will tell if the catalytic converter concept will prove successful and result in a durable, reliable means of controlling emissions when operated and maintained by the public over a wide range of conditions, e.g., inoperative partially open automatic chokes, dirty air filters, misfiring plugs, overly rich carburetor can poison the catalyst.

   We believe that the closed-loop stoichiometric fuel control system in itself is desirable, since it will keep the engine in tune which will result in a more efficient operation and consequently save fuel. However, this system will require the development of a durable and reliable O_2 sensor for the feedback signal. We consider this concept to have medium technical risk available in the 1981-1984 time frame. A major problem with the catalytic converter system is that the catalyst will probably have to be replaced at 50,000 miles which will cost the owner approximately $100-$125. This will make the total system less cost-effective. Furthermore, if electronic fuel injection system is used, the initial cost and maintenance cost will increase. In our opinion, the result is of questionable cost-effectiveness. The catalytic converters use noble metals, such as platinum or palladium, which must be imported – another undesirable feature.

4. Another design concept consists of the same system described in item 3 with the substitution of a continuously variable transmission. We have included this concept to permit the evaluation of the closed-loop system operating under ideal transmission-matching conditions. Fuel reduction percentage is 34-37%. However, offsetting this fuel saving is the high risk of two unproven systems being combined. Therefore, we do not see this system becoming available to the public before the 1981-1984 time period. Development of the system would entail solving all the problems associated with providing a durable engine under long-term, high-loading conditions.

5. A light-weight vehicle with a stratified-charge engine and equipped with a four-speed automatic and torque converter lockup is another design concept. We believe this concept has an inherent high risk factor, although the percentage of fuel usage reduction is potentially 30-35%. The concept is not so cost-effective as that of other engines. In addition, the engine would have to be developed as a reliable power plant

with a degree of driving flexibility not yet achieved in practice. Furthermore, the system would require a fuel injection system and a spark ignition system which would probably have high maintenance and repair costs. However, development of this concept is being widely pursued, and we believe that answers should be available in the near term concerning whether further progress will continue. The engine does have the capability of operating over a wide range of octane numbers and with different types of fuel which is a distinct advantage. It is not clear whether a catalytic converter will be necessary to control the exhaust emissions from this engine and, if so, whether the use of exhaust gas recirculation will be necessary, and how this will affect the fuel economy.

6. Another design concept consists of the same engine and vehicle concept described in item 5, except equipped with a continuously variable transmission. We consider that this concept has the highest technical risk and will not be available to the public before the 1982-1984 period. However, our estimates indicate that fuel usage reduction percentage could approximate 39-42%.

7. Of all the concepts examined in this study, we consider the light-weight vehicle with radial tires, a diesel engine, a four-speed automatic transmission, and torque converter lockup, to have the greatest potential for fuel savings and with a medium technical risk. This system represents a good cost-effective solution, being based on a concept which has been well proven in the past in many light-weight duty vehicles. The problem connected with it is designing an engine that will meet the weight constraints, while providing performance currently available in the standard and compact size reference vehicles. We believe that the maintenance and problems of engine design, noise, and cold start are solvable within the time frame. We also believe that this engine would be reliable and have low maintenance cost. We do not see a problem in changeover to the large scale distribution of diesel fuel; however, this aspect must be studied.

8. Another design concept is the same system as described in item 7, except that it is equipped with a continuously variable transmission. We consider the combination of the light-weight diesel with a continuously variable transmission to be a high risk, simply because of the combination of the unproven aspects of both designs. However, as in the other concepts discussed, effort in developing this transmission should prove advantageous for the diesel engine also.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 FUEL ECONOMY IMPROVEMENTS

5.1.1 Conclusions

5.1.1.1 Conclusions Relating to Program Goals — The goal of a 43% improvement in fuel economy (mpg), or 30% reduction in fuel usage (gpm), for the compact(c) and standard(s) size vehicle appears attainable by the early 1980's within the constraints of this program.

- Since the initial conception of the need for this study and during the period that the work was actually conducted, there has been a tremendous shift in the buying preference of the public across the Nation. The trend has changed from the standard-size (4200 lb), relatively high-acceleration performance, large-engine cars to compact and smaller sizes with smaller displacement engines. This change in car mix will, in itself, reduce the Nation's fuel consumption. However, since there will always be a need for the larger vehicles — either passenger vehicles or light-duty trucks — the study results are still useful in understanding what can be done to improve fuel economy through technological hardware innovation. Furthermore, the technological improvements which we examined in this study could be applied to smaller cars with approximately the same relative gains.

- Our theoretical analysis revealed that, while fuel economy has always been considered important, until the combined impact of regulatory safety/emission controls on fuel economy and the increased price of fuel, there has been no real incentive to depart from current standard automobile designs. In fact, most approaches to improving fuel economy which did not reduce car size or performance (acceleration) have been partially or fully developed, only to be dropped because of the added initial cost to the first owner with no potential for payback at fuel costs of $0.25-$0.30/gal.

- Because of pressures in the marketplace — in addition to increasing the production capacity for small cars — automobile companies and associated industries are expending major efforts to improve fuel economy in the near term and in the future.

- Implementing innovations which reduce fuel usage might be accelerated (a) by demonstrating some approaches which prove the validity of the concepts, and (b) by obtaining more basic knowledge of their actual cost-effectiveness and potential acceptance by the public.

5.1.1.2 Technological Improvements Resulting in Fuel Economy Gains — All individual innovations yielding substantial gains in fuel economy without changing either size car performance, or driver habits, may be grouped into one of three major technological areas:

1. Changes in vehicle structure which reduce weight, aerodynamic drag, and rolling resistance;

2. Improved matching of the engine coupling to the road load by use of modified transmission now in use, or continuously variable transmissions presently being developed; or

3. Near-term (mid-1970's) improvement in present engine operating efficiency or substitution of conventional gasoline engines by the diesel or stratified charge-type engines for the long-term 1980's.

5.1.1.2.1 Improved Light-Weight Body and Chassis with Radial Tires – In all the approaches studied with the objective of realizing this goal, we assumed the development of body and chassis construction of 10% less weight, 10% less frontal area, 20% less aerodynamic drag coefficient, and the substitution of radial tires for belted bias tires. The combined contribution of these improvements accounts for approximately 9 (standard) to 13 (compact) % mpg gain [8 (standard) to 12 (compact) % gpm reduction]. These improvements have been recognized by the automobile manufacturers and will be incorporated in new cars at the time of major body change – somewhere in the 1976-1978 period.

5.1.1.2.2 Improved Matching of Engine to Road Load – In all approaches studied, we recognized the importance of improving the matching of power plant to the drive train. In this regard, we considered two general types of improved transmissions:

- *Automatic Four-Speed Transmission with Torque Converter Lock-Up* – This change would consist of adding a gear to make a four-speed transmission (overdrive) and a lock-up device for the torque converter to reduce hydraulic losses, resulting in about a 10 (standard) to 15 (compact) % mpg gain [9 (standard) to 13 (compact) % gpm reduction]. These improvements are now being considered by the manufacturers and could be made available by the 1976-1978 period.

- *Continuously Variable Transmission (CVT)* – While either the traction-type or hydromechanical-type CVT will contribute approximately 20 (standard) to 25 (compact) % mpg gain [16 (standard) to 20 (compact) % gpm reduction], each involves both a high technical risk and a long development time before it could be fully implemented sometime in the early 1980's. The CVT approach has received a great deal of attention and effort over the years, but until now the low cost of fuel has not warranted the full development of this type of transmission. Furthermore shift logic and sensor control systems require development.

5.1.1.2.3 Improved Engine Efficiency and Fuel Usage – Improving engine fuel usage may be accomplished by two general approaches which can be included within the constraints of this study:

- Improve the fuel usage of the present spark ignition engine by either operating it at the stoichiometric air/fuel ratio by a closed-loop control, or under lean air/fuel ratio conditions. Either of these methods yields about a 5-10% mpg gain for the near term and represents an interim solution to offset losses in fuel economy until other concepts are developed and become available.
- Extend the concept of the conventional piston engine for light-duty passenger car use by developing the stratified-charge engine and particularly a light-weight diesel engine. We believe that the stratified charge engine is less viable than the diesel because of a lack of proven road flexibility, increased complexity, and lower potential for fuel economy gain; i.e., 17 (standard) to 18 (compact) % mpg gain for the stratified charge versus 20 (standard) to 25 (compact) % mpg gain for the diesel.

5.1.1.3 Most Cost-Effective Approach – Maximum gains can be made if the individual innovations are combined using a total systems approach which we have attempted in this study.

The most cost-effective approach – with medium technical risk – to achieving the study goals involves use of a light-weight diesel engine, combined with a four-speed automatic transmission, a torque converter equipped with lock-up mounted in a light-weight improved body, and a chassis equipped with radial tires. Theoretical analysis indicates fuel economy gains of 44 (standard) to 50 (compact) % mpg or fuel usage reduction of 36 (standard) to 40 (compact) % gpm.

5.1.2 Recommendation

We recommend that industry and developers be encouraged (1) to investigate further the three improvement areas listed in Section 5.1.1.2 and (2) to proceed with development of promising innovations. Specifically, we recommend that –

- The present EPA/AAPS program for assessing the light-weight, high-speed diesel be continued to the development stage of the most promising diesel concept.
- The U.S. Army Tank Automotive Command Program concentrate on the development of stratified charge engines for light-duty military vehicle service and evaluate them completely for their applicability to non-military passenger car requirements.
- A joint effort which is currently being considered by the AAPS/EPA between the Government and industry be undertaken to evaluate separately the continuously variable transmission – both the traction and hydromechanical types.

- The evaluation of the lean-burn engine concept be continued and approaches which may have been stopped for various reasons be re-examined in light of fuel economy goals. Table 4-16 of the main report identifies specific developers and shows examples of their different approaches.

- Finally, a survey of materials application useful for improving weight reduction be undertaken. This survey would require a detailed analysis of plastics, glass, aluminum, and others, and the implications of their utilization on a cost-effective basis, considering fuel economy gains, initial cost, and natural resource depletion, plus problems related to scrap recovery.

5.1.3 Factors to Consider in Introducing Technological Improvements

5.1.3.1 Technological Risks – These risks range from –

- **Low** – for weight, drag, rolling resistance, and improved present type of automatic transmission, to

- **Medium** – for developing lean-burn and diesel engines, to

- **High** – for closed-loop exhaust emission-controlled catalytic converter engines, stratified charge engines, and continuously variable transmissions because of required durability and higher maintenance costs.

5.1.3.2 Lead Time – Lead time for introducing improvements does not follow the degree of risk necessarily, e.g.:

- Near Term – Lightened body, chassis, tires, and present automatic transmission; next major body style change (1977-1979); lean-burn and closed-loop approach (1977-1980);

- Long Term – Stratified charge, diesel, and continuously variable transmission (1981-1984).

5.1.3.3 Cost Effectiveness – Cost effectiveness is a yardstick used to measure the overall monetary benefit of an improvement, i.e., benefits (savings) over the life cycle of the car (100,000 miles over 10 years). To be considered cost-effective, these benefits should exceed the overall cost. At fuel costs of $0.75/gal:

- Individual improvements that are cost-effective include the body chassis, transmissions, tires, and the lean-burn and diesel engines.

- An individual improvement that just meets the cost-effective test is the stratified-charge engine.

- An individual improvement that fails the cost-effective test is the closed-loop exhaust, emission-controlled engine.

5.1.3.4 Customer Acceptance

5.1.3.4 Customer Acceptance – Customer acceptance would depend on the degree of development and cost of fuel at the time of introduction, since there could be some sacrifice in driveability, durability, and repair/maintenance costs. We rank the improvements as follows:

- *High Acceptance* – Less weight, drag, improvement of present-type automatic transmission and radial tires; diesel engine, if odor problem is solved.
- *Medium Acceptance* – Continuously variable transmission, because of noise and engine reaction; lean burn, because of poor driveability and possible need for high octane or leaded fuels.
- *Low Acceptance* – Closed-loop exhaust emission control, because of durability and replacement costs of catalytic converter and high initial cost with low fuel economy gains; stratified charge, because of high initial cost, possible poor driveability response and high maintenance cost, particularly if catalytic converters are required.

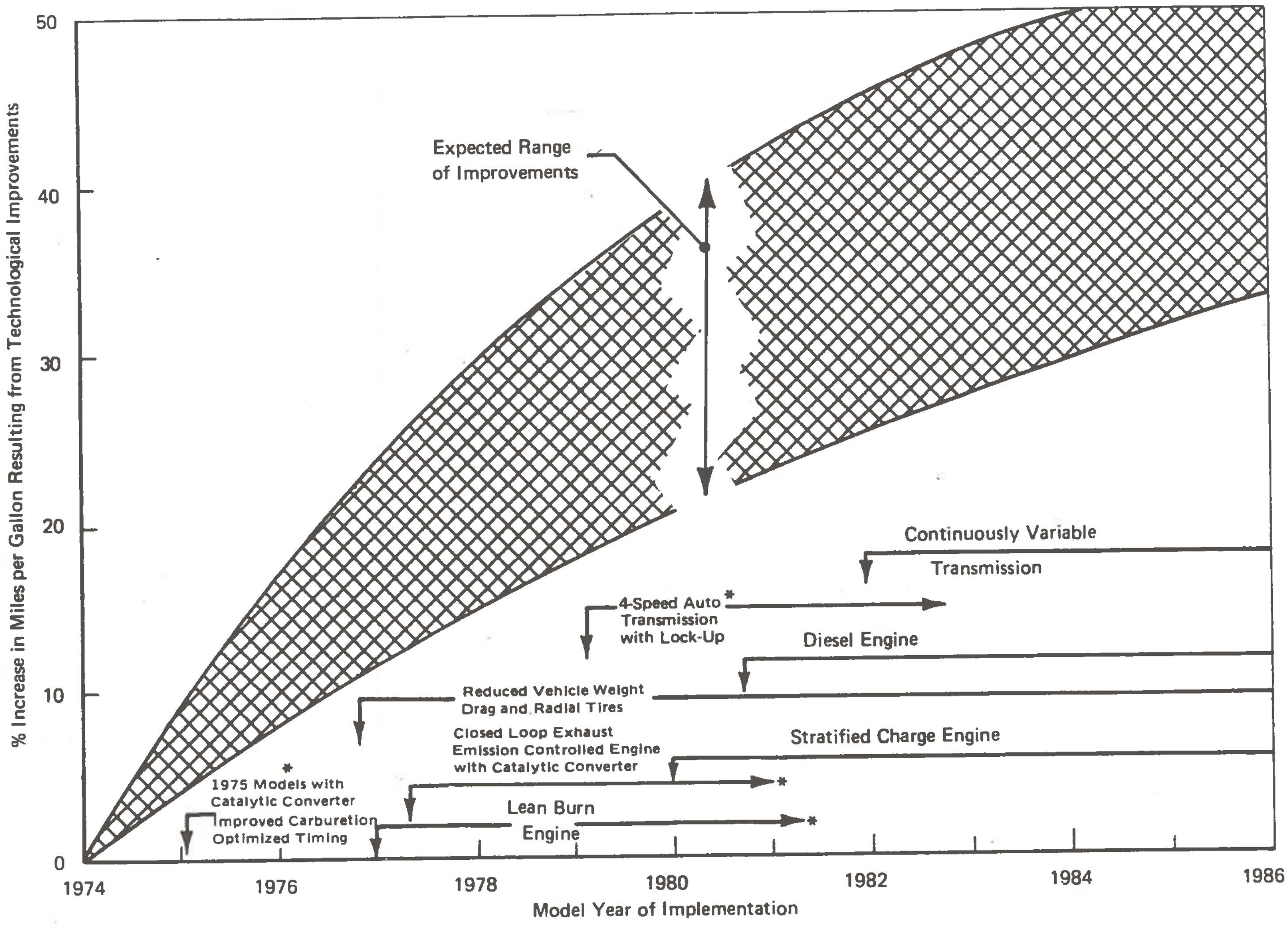
5.1.3.5 State of Development and Time Phasing – The improvements investigated are either under development or appear ready for production using both lighter materials and the production technology/skills associated with present-day piston engines, automatic transmissions, fuel/ignition systems, and sheet metal manufacturing. Therefore, we do not see that the candidate improvements will have the degree of impact on manufacturing facilities or labor skills that the introduction of alternate power sources, which depart from present piston engine technology – such as Wankel engines, steam engines, gas turbines, or Stirling cycle engines – would have, even if these alternative power sources could approach the goals of this study. We did not include the alternative power sources in this study.

A time-phased assessment of the improvements discussed is presented in Figure 5-1. This figure shows a range of feasible percentages of improvement in fuel economy (mpg) from 1974 to 1984 and the range of time required to reach full-scale production of units to be incorporated into complete vehicle systems. Another way of displaying this information is shown in Table 4-4 which shows that – based on $0.75/gal – the owner's annual total savings would range from $27 to $146, saving from 130 to 316 gallons of fuel per year. The estimated maximum increase in initial cost for a complete improved vehicle system would vary from $430 to $970 for the standard-size car and from $305 to $790 for the compact-size car (see Tables 4-2 and 4-3).

5.2 EMISSION CONSTRAINTS

5.2.1 Conclusion

The fuel economy of the standard spark-ignited engine vehicle has been materially reduced (1) by the use of emission control measures, such as retarded ignition timing, decreased compression ratio, and the exhaust gas recirculation air pump, and (2) by the increase in engine size to offset subsequent loss in performance.



* These may be interim solutions which might be replaced by long-term improvements.

FIGURE 5–1 POTENTIAL PERCENT IMPROVEMENT IN FUEL ECONOMY RESULTING FROM TECHNOLOGICAL IMPROVEMENTS VERSUS TIME OF IMPLEMENTATION

We believe that NO_x is the hardest of the exhaust pollutants to control in the spark-ignition engine, while maintaining engine efficiency as based on control equipment used in vehicles produced to date. This type of equipment includes non-proportional exhaust gas recirculation (EGR) valves which are counteractive to improved fuel economy, lowest system cost, and durability. However, there are developments under way which indicate that, if EGR valves which recirculate exhaust gases proportional to engine load are used, then fuel economy losses may be minimized or improved.[5]

5.2.2 Recommendation

We recommend that the study being conducted by the National Academy of Science on automotive exhaust pollutants and emission standards be carefully considered in any future effort to modify or maintain present required standards, and also that these standards be fixed on a long-range basis. This will enable engine developers to work out the compromises which offer the best cost benefits considering ambient air, energy conservation, and vehicle cost per mile for the consumer.

5.3 VEHICLE FUEL ECONOMY MEASUREMENT

5.3.1 Conclusions

There is no uniform method for determining fuel consumption on a yearly basis within the industry or Government which allows a car owner to assess the amount of fuel consumed by his vehicle in meeting his particular needs; that is, a method comparable to describing performance as accelerating from 0 to 60 mph in so many seconds. The need to develop such a uniform, easily understood rationale for determining fuel economy will become increasingly important as fuel costs increase. Many misconceptions arise about gains or losses in fuel economy, because of this lack of a standard measurement method. This makes comparative evaluations very difficult, particularly so if in performing fuel economy evaluations and comparisons, equal performance (ability to accelerate) is not maintained before and after the incorporation of changes which affect fuel economy on vehicles of the same size and weight.

The federal driving cycle, developed for determining amounts of pollutants emitted during vehicle test, was not primarily intended to provide actual fuel economy information. However, it does provide a reasonable measure of urban fuel economy, but it is not a reasonable measure of highway economy because it does not include sustained speeds and accelerations encountered on U.S. rural or interstate highways.

We are expecting an increased effort within both industry and the Government to establish standards, uniform tests, and driving cycles for determining realistic tank mileage (mpg) results – perhaps even yearly fuel consumption techniques as well. An SAE committee is presently considering the development of a uniform fuel economy measurement procedure.

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5. Gumbleton, J.J., Bolton, R.A., and Lang, H.W., "Optimizing Engine Parameters with Exhaust Gas Recirculation, SAE Paper 740104, Feb. 25-March 1, 1974.

Finally, because of the lack of standards and uniform tests, it is very difficult to obtain useful experimental data from innovators on emission levels and, at the same time, performance and fuel usage data.

5.3.2 Recommendation

We recommend that every effort be made to expedite the establishment of standards, tests, and driving cycles which will permit manufacturers of improved vehicles to measure fuel economy and yearly fuel usage under uniform and comparable conditions.

5.4 SIMULATION OF VEHICLE FUEL ECONOMY AND PERFORMANCE

5.4.1 Conclusion

The simulation modelling technique developed for this program – similar to others used by industry and Government – is very useful in determining the effect of a change relative to a reference base vehicle or engine. The results from such simulation modelling appear to provide credible results. However, the simulation technique is only a tool and does not replace the need for experimental testing and engineering evaluation programs for comparison purposes.

Similar to the lack of a uniform set of standards and test procedures for measuring vehicle fuel consumption, no uniform method of engine testing for fuel consumption data, including the effects of emission control devices, accessories, exhaust systems, and the like, is being used consistently. This lack prevented us from fully evaluating the proposed improvements on a comparable basis.

Simulation techniques, while providing valuable indications of whether an innovation would effect an improvement in fuel economy or performance, are desirable and probably necessary; actual validation tests have to be made somewhere downstream.

5.4.2 Recommendations

We recommend that the work being done to establish vehicle fuel economy measurement standards, tests, and driving cycles be extended to include a similar set of standardized criteria to serve as guidelines in performing powerplant tests, so as to provide data for simulating vehicle fuel economy and emission levels under different operating conditions.

We recommend that a technique be developed – similar to the technique that is used to predict the interaction between fuel economy and performance – for predicting the interactions between emission control and fuel economy. This technique should provide the predictive tool for examining potential improvements in vehicle designs under development and be supplemented by actual testing.

Summary Analysis of the Individual Improvements against the Qualitative and Quantitative Constraints for Both Compact and Standard Size Vehicles

Tables 5-1 through 5-9

		STANDARD SIZE									COMPACT SIZE									
					ESTIMATED INCREMENTAL (Δ) COSTS FOR 10 YEARS, 100,000 MILES $								ESTIMATED INCREMENTAL (Δ) COSTS FOR 10 YEARS, 100,000 MILES $					
MODIFICATIONS	CONCEPT DESCRIBED IN SECTION	MILEAGE IMPROVEMENT % (mpg)	FUEL REDUCTION % (gpm)	FUEL SAVED IN 10 YEARS (100,000 MILES)	Δ INITIAL COST TO FIRST OWNER	Δ REPAIR AND MAINTENANCE COST PER YEAR TO FIRST OWNER	Δ REPLACEMENT COSTS	TOTAL Δ COSTS	ESTIMATED NET SAVINGS BASED ON 10 YEARS, 100,000 MILES @ 75¢ / GALLON	MILEAGE IMPROVEMENT % (mpg)	FUEL REDUCTION % (gpm)	FUEL SAVED IN 10 YEARS (100,000 MILES)	Δ INITIAL COST TO FIRST OWNER	Δ REPAIR AND MAINTENANCE COST PER YEAR TO FIRST OWNER	Δ REPLACEMENT COSTS	TOTAL Δ COSTS	ESTIMATED NET SAVINGS BASED ON 10 YEARS, 100,000 MILES @ 75¢ / GALLON	TIME FRAME
1 10% Reduction in Frontal Area	4.3.7	1.3	1.2	83	–	–	–	–	62	2.11	1.97	104	–	–	–	–	78	1977–1979
2 20% Reduction in Drag Coefficient	4.3.7	2.6	2.4	164	–	–	–	–	124	4.22	3.96	208	–	–	–	–	156	1977–1979
3 10% Weight Reduction	4.3.8	2.7	2.5	172	100	–	–	100	29	3.4	3.2	169	80	–	–	80	46	1977–1979
4 Radial Tires	4.3.8	2.5	2.3	158	70	–	(60)	10	108	3.5	3.3	174	60	–	(40)	+20	110	Presently Available
5 Total of Items 1 – 4		9.1	8.4	558	170	–	(60)	110	308	13.2	12.4	653	140	–	(40)	100	350	1977–1979

	STANDARD SIZE										COMPACT SIZE							
					ESTIMATED INCREMENTAL (Δ) COSTS FOR 10 YEARS, 100,000 MILES $									ESTIMATED INCREMENTAL (Δ) COSTS FOR 10 YEARS, 100,000 MILES $				
MODIFICATIONS	CONCEPT DESCRIBED IN SECTION	MILEAGE IMPROVEMENT % (mpg)	FUEL REDUCTION % (gpm)	FUEL SAVED IN 10 YEARS (100,000 MILES)	Δ INITIAL COST TO FIRST OWNER	Δ REPAIR AND MAINTENANCE COST PER YEAR TO FIRST OWNER	Δ REPLACEMENT COSTS	TOTAL Δ COSTS	ESTIMATED NET SAVINGS BASED ON 10 YEARS, 100,000 MILES @ 75¢ / GALLON	TIME FRAME	MILEAGE IMPROVEMENT % (mpg)	FUEL REDUCTION % (gpm)	FUEL SAVED IN 10 YEARS (100,000 MILES)	Δ INITIAL COST TO FIRST OWNER	Δ REPAIR AND MAINTENANCE COST PER YEAR TO FIRST OWNER	Δ REPLACEMENT COSTS	TOTAL Δ COSTS	ESTIMATED NET SAVINGS BASED ON 10 YEARS, 100,000 MILES @ 75¢ / GALLON
6 Standard Engine with Optimized Spark Setting, Improved Carburetor, Catalytic Converter	4.3.3.1	7.5 (5–10%)	6.8	468	125 (100–150)	10/Yr	100 End 3rd Year	325	26	1977–1979	7.5	6.8	358	125 (100–150)	20/yr.	100	1425	(56)
7 Lean Burn Engine with Improved Carburetor or Fuel Injection, Thermal Exhaust Reactor, Modulating E.G.R., Optimized Ignition System Possible Catalytic Converter	4.3.3.2	7.5 (5–10)	6.8	468	60 (30–90)	10/Yr	60	220	131	1977–1979	7.5	6.8	358	60 (30–90)	10/yr	–	160	109
8 Closed-Loop Exhaust Emission Control System, Stoichiometric A/F Ratio, Optimized Ingition System	4.3.3.3	10% (5–15)	9%	619	300 (250–350)	30/Yr	100 End of 3rd Year	700	* (233)	1977–1979	10	9	474	300 (250–350)	30/yr.	100	700	* (344)
9 Turbocharged Spark-Ignition Engine	4.3.3.4	7.5 (5–10)	6.8	468	200 (150–250)	30/Yr	–	500	* (149)	Presently Available	7.5	6.8	358	200 (150–250)	30/yr.	–	500	* (231)
10 Stratified Engine, Open-Chamber Type Only may Require Catalytic Converter	4.3.3.5	17.5 (15–20)	15.0	1032	500	30/Yr	–	800	* (26)	1977–1979	18	15	791	400	30/yr	–	700	* (107)

* Amount in ( ) is unrecovered cost and indicates that these individual improvement concepts are not cost effective when gasoline averages 75¢/gal during 10 years (100,000 miles).

MODIFICATIONS	CONCEPT DESCRIBED IN SECTION	STANDARD SIZE								TIME FRAME	COMPACT SIZE							
		MILEAGE IMPROVEMENT % (mpg)	FUEL REDUCTION % (gpm)	FUEL SAVED IN 10 YEARS (100,000 MILES)	ESTIMATED INCREMENTAL (Δ) COSTS FOR 10 YEARS, 100,000 MILES $				ESTIMATED NET SAVINGS BASED ON 10 YEARS, 100,000 MILES @ 75¢ / GALLON		MILEAGE IMPROVEMENT % (mpg)	FUEL REDUCTION % (gpm)	FUEL SAVED IN 10 YEARS (100,000 MILES)	ESTIMATED INCREMENTAL (Δ) COSTS FOR 10 YEARS, 100,000 MILES $				ESTIMATED NET SAVINGS BASED ON 10 YEARS, 100,000 MILES @ 75¢ / GALLON
					Δ INITIAL COST TO FIRST OWNER	Δ REPAIR AND MAINTENANCE COST PER YEAR TO FIRST OWNER	Δ REPLACEMENT COSTS	TOTAL Δ COSTS						Δ INITIAL COST TO FIRST OWNER	Δ REPAIR AND MAINTENANCE COST PER YEAR TO FIRST OWNER	Δ REPLACEMENT COSTS	TOTAL Δ COSTS	
11 Light-weight Diesel	4.3.3.6	20.0	16.2	1135	600	–	–	600	251	1977–1979	25	20	1054	500	–	–	500	291
12 4-Speed Auto. Transmission with Optimized Shift Logic and Lockup, Torque Converter	4.3.4	10.0	9	619	75	–	–	75	389	1977–1979	15	13	685	65	–	–	65	449
13 Continuously Variable Transmission and Heavy-Duty Engine, Engine	4.3.4.11	20	16.2	1135	200	–	–	200	651	1977–1979	25	20.0	1054	150	–	–	150	641
14 Constant-Speed Drive for Accessories without Air Conditioning	4.3.5	1%	.96	65	25	–	–	25	24	Presently Available	1	.9	250	25	–	–	25	10
15 With Air Conditioning at one-third Duty Cycle	4.3.5	3%	2.9	200	25	–	–	25	125	1977–1979								

MODIFICATIONS	TECHNICAL AND MANUFACTURABILITY PROBLEMS	DURABILITY AND MAINTAINABILITY	CUSTOMER OPERATING CONSIDERATION	REMARKS
1 10% Reduction in Frontal Area	No Cost Penalty if Done With Model Change — Requires Extensive Redesign of Body and Possible Change in Chassis	Would Be Equal to Present Production 1973 Reference Vehicle	Seating Space a Difficult Problem to Overcome	Due to Extensive Sheet Metal and Body Tooling Required, Could be Done Only at Time of Major Body Change, Care Must be Taken to Prevent Aerodynamic Lift
2 20% Reduction in Drag Coefficient	Same as Above Except Restyling for Sheet Metal Changes, a Full 20% Reduction May be Difficult to Achieve on First Model Change	Would be Equal to Present Production 1973 Reference Vehicle	Reduces the Wind Resistance But Might Sacrifice Some Passenger Room and Luggage Space	Must be Done at Time of Complete Change of Body; Otherwise Tooling Costs are Prohibitive
3 10% Weight Reduction	Same as Above Substitution of Aluminum May Increase Cost in Some Areas and Require Development of Joining Techniques, Forming, etc.	Would be Equal to Present Production 1973 Reference Vehicle, Except that Repairability of Damaged Aluminum Sheet Metal More Difficult than Steel	Customer Would Have Same Performance with Improved Economy if Axle Ratio is Adjusted	Axle Ratios Below 2.7 are not Desirable; 2.5 Ratio can be Made, but that is the Limit of Present Designs
4 Radial Tires	No Major Problems Except Expansion of Production Facilities if Used on 100% Production	Longer Tire Life of 50 to 100%, Depending on Driving Conditions; Greater Reliability Due to Steel Belting	Customer Would Notice No Change, Except Reduction in Fuel Consumption, Particularly in Highway Driving	Radial Tires will Increase in Use as an Option, but 100% Production Would Require Increase in Plant Capacity which Might not be Completed Before 1978
5 Total of Items 1 – 4	A Comprehensive Systems Approach for Engineering is Required to Optimize into an Integrated Design	Should be Equal to 1973 Vehicle, But May Require New Skills for Repairing Damaged Aluminum Panels	Customer Should Accept Changes if Conscious of Savings Accruing from them	All Above Improvements are Additive and Offer an Excellent Cost-Effective Solution

MODIFICATIONS	TECHNICAL AND MANUFACTURABILITY PROBLEMS	DURABILITY AND MAINTAINABILITY	CUSTOMER OPERATING CONSIDERATION	REMARKS
6 Standard Engine with Optimized Spark Setting, Improved Carburetor, Catalytic Converter	Durability of Catalyst Under a Wide Variety of Operating Conditions with Engines in Various Stages of Time	Durability Requirements of 50,000 Miles Must be Met for Certification with Minimum Maintenance which is not Proven at Present, Indications are that Catalytic Converter Must be Replaced After 50,000 Miles – Cost: $35–$100	Catalyst Allows Optimizing Carburetor and Ignition Timing for Best Performance and Economy; Present Data Indicates About 5–15% Gain in Economy Marginally Cost Effective Manufacturers Committed to 1975 Cars, Probably be Used as Stop Gap Solution	Uses Noble Metals; e.g., Platinum and Palladium, which have to be Imported from So. Africa, Poor Cost-Effective Solution
7 Lean Burn Engine with Improved Carburetor or Electronic Fuel Injection, Thermal Exhaust Reactor, Modulating E.G.R., Optimized Ignition System Possible Catalytic Converter	Appears to be Low Risk and should be Possible within 4 – 5 Years, May Require Leaded Fuels or Higher Octane Fuel	Durability not yet Proven but Should Equal Present Engine – However, Variable Venturi Carburetor May Require Slightly More Maintenance; Thermal Reactor More Durable than Catalytic Converter	Makes It Possible to Burn Lean Mixtures with Little Cycle-to-Cycle Variation Thus Free from "Surge"; Gives Improved Part Load Economy – High Cost Effective Engine Improvement Available in Near Term	Fuel Injection (F.I.) Only Proven System for Extending Lean Flammability Limits to 20–22 to 1 Air Fuel Ratio. Ethyl Corp.'s 3-Barrel Carburetor Goes Only Part Way, but Should Receive Consideration as Interim Solution, to Prove Principle
8 Closed-Loop Exhaust Emission Control System, Stoichiometric A/F Ratio, Optimized Ingition System	No Data to Indicate that E.F.I. will Improve Fuel Economy Except at Higher Loads and Engine Speeds. Difficult to Meter Fuel Accurately at Idle and Light Loads; Fuel Preparation Poor Due to Short Path From Intake Valve into Cylinder	Durability and Reliability Less Than with Conventional Carburetors, Maintenance Higher, Catalytic Converter Durability not Proven in Hands of Public, Closed-Loop Concept Excellent if it Really Works within Narrow Limits	Save Fuel on Deceleration Due to Use of Fuel Shutoff; Better Warmup and Cold Driveability; Very Responsive on Acceleration	Electronic Fuel Injection Excellent for High Performance Vehicles at Present. Progress is being Made and it is Worth Further Development for Lowering Exhaust Emissions and Getting Driveability This is a Natural Outgrowth of Catalytic Converter System to be Introduced on 1975 Models Poor Cost-Effective Solution
9 Turbocharged Spark-Ignition Engine	Engine Durability May be Less Due to Increase in Power; Octane Requirement Increase at High Speeds; Requires Lower Compression Ratio; Reduced Engine Torque Requires Higher Numerical Axle Ratio	Higher Engine Output Requires More Expensive Exhaust Valves for Durability; Addition of Turbocharger and Blown Carburetor Reduces Reliability and Increases Maintenance	No Experimental Data to Indicate This Combination Would Improve Economy if Performance and Driveability are Equal. Lower Compression Ratio and Higher Axle Ratio Increase Fuel Consumption	Not Worth Developing Unless Test Information Indicates Breakthrough; Water-Alcohol Injection Not Satisfactory Solution for Reducing Octane Requirement Will not Consider Further for this Study
10 Stratified Engine, Open-Chamber Type Only may Require Catalytic Converter	Problem in Maintaining Driveability, Economy, Performance and Emission Control Over Whole Speed and Load Range; Maintaining Engine Power at Higher Engine Speeds	Driveability can be made Equal to Present Conventional Engines, but Reliability is Reduced Some Due to Extra Parts; Additional Maintenance Likely; Durability with F.I. and Catalytic Converter not Proven	Customer May Not Accept Driveability or Marginal Cost Effectiveness; Low Octane Fuel May be Used	Not a Proven Production Concept but Appears to be Worth Further Study and Development so that Cost-Benefits Could be Compared to Other Systems. U.S. Army Tank Command Funding Extensive Program for Military Multi-Fuel Open-Chamber T.C.C.S.-Type Engines

MODIFICATIONS	TECHNICAL AND MANUFACTURABILITY PROBLEMS	DURABILITY AND MAINTAINABILITY	CUSTOMER OPERATING CONSIDERATION	REMARKS
11 Light-weight Diesel	For Passenger Car Use Problems Relate to Controlling Engine Noise, Smoke and Odor; Cold Starting at 0ºF or Lower Requires Special Attention	No Light-Weight Design Available So Must be Developed and Proven; Present Heavy Designs Very Durable and Reliable and Require Minimum Maintenance	Diesel Fuel Not Readily Available in Service Stations at Present; Diesels Must Be Kept in Good Mechanical Shape to Maintain Power, Economy, and Minimize Smoke and Odor However this Should be Less than Catalytic Maintenance of Future	Proven Concept But Would Require Extensive Effort to Develop a Diesel that Would Meet Present Gasoline Engine Weights; a Weight Penalty Will Probably be Incurred, High Cost-Effectiveness Probably Best Choice to Replace Spark Ignition for 1980's
12 4-Speed Auto. Transmission with Optimized Shift Logic and Lockup, Torque Converter	Lock-up Clutch Must be Automatic with Either Centrifugal or Converter Charging Pressure Control or Combination of Both; Carburetor Enrichment Required for Driveability; Torsional Vibration Problems in Lock-Up Must be Investigated	More Complicated, Would Tend to Reduce Durability and Reliability and Increase Maintenance, But Should Equal Present Transmission when Fully Developed	Customer Acceptance Problem Due to Sharper Shifts With Converter Locked Out; Should Give Improved Economy and be Acceptable	All Comments are for Lock-up Only as 4-Speed Gain Over 3-Speed Must be Proven by Test with that as the Only Variable – Very High Cost-Effectiveness if Properly Matched to Engine
13 Continuously Variable Transmission and Heavy-Duty Engine, Engine	Durability Unknown Especially When Used with 350 Cu. In. or Larger V-8 Engines	Meeting Durability Requirements Difficult; Extensive Development Effort Required; No Reduction in Life Below Present Automatics Acceptable	Creates Problem with Control of Emissions Due to Higher Load Factor on Engine; Engine Durability Must be Evaluated; Octane Requirement Higher at Low Engine Speeds May be Problem; Noise of Transmission and Engine being Different than Present Vehicle Must be Considered and Made Acceptable to Customer	Better Fuel Economy at Constant Speeds, But May Give Only Small Gain in City Traffic or EPA Schedule, Very High Cost-Effectiveness Development Should be Encouraged, Usable on All Engines
14 Constant-Speed Drive for Accessories without Air Conditioning	Unit Must be Developed; Not Presently Available	Unknown	Unknown Noise Could Present Major Acceptance Problem	Not Cost-Effective, Will not Consider Further
15 With Air Conditioning at one-third Duty Cycle	Unit Must be Developed, Not Presently Available, Cost for Unit Not Proven	Unknown	Same as Above Unknown, Probably Not a Problem	Probably Not Cost-Effective if Much Over $25–$50, and if Air Conditioning Runs on Light Duty Cycle, Will not Consider Further

MODIFICATIONS	COMPLIANCE WITH CONSTRAINTS	CHANCE FOR SUCCESS	GROWTH POTENTIAL	PERFORMANCE	PHYSICAL CONFIGURATIONS			EFFECT ON OTHER SUBSYSTEMS		
					SIZE	WEIGHT	COMPLEXITY	COOLING	ELECTRICAL	MECHANICAL
1 10% Reduction in Frontal Area	Construction of Doors must Meet Safety Requirements	Low Risk	Low	Excellent	Smaller	Probably Less	Equal	None Radiator Core May Present Problem	None	Chassis Must be Investigated Thoroughly to Incorporate this Improvement
2 20% Reduction in Drag Coefficient	Yes	Low Risk for 10% Reduction, Medium Risk for 20%	Low	Excellent	Equal	Equal	Equal	None	None	None
3 10% Weight Reduction	Yes – However, must be engineered for safety	Low Risk	Low	Excellent	Equal	Less by 10%	Equal	None	None	Axle Ratio Must Be Adjusted for Equal Performance
4 Radial Tires	Yes	Low Risk	Low	Excellent	Equal	Equal	Equal	None	None	Requiring Change in Chassis, Spring Height, Shock Absorbers, Calibration, Engine and Body Mount Tuning for Proper Handling
5 Total of Items 1 – 4	Yes	Low Risk	Low	Excellent	Smaller	Less by 10%	Equal	None Except for One Above	None	

MODIFICATIONS	COMPLIANCE WITH CONSTRAINTS	CHANCE FOR SUCCESS	GROWTH POTENTIAL	PERFORMANCE	PHYSICAL CONFIGURATIONS			EFFECT ON OTHER SUBSYSTEMS		
					SIZE	WEIGHT	COMPLEXITY	COOLING	ELECTRICAL	MECHANICAL
6 Standard Engine with Optimized Spark Setting, Improved Carburetor, Catalytic Converter	Catalytic Poisoning or Degradation May Cause Loss of Emission Control	Medium Risk	Low	Should be Equal to or Better than 1973	Equal	Equal Except for Converter	More Complex Especially Catalyst	None	High Intensity Electronic Ignition Required Precise Timing	Requires More Precise Caburetion & Tune
7 Lean Burn Engine with Improved Carburetor or Electronic Fuel Injection, Thermal Exhaust Reactor, Modulating E.G.R., Optimized Ignition System Possible Catalytic Converter	Close to Goals of this Study; Must be further evaluated to determine if HC std. can be met; Might Require Cat. Conv.	Medium Risk	Low	May have Stumble and Poor Throttle Response if Maximum Fuel Economy is the Goal	Equal	Equal	Same as 1973	None	None	Carburetor More Precise, Thermal Reactor Required, Fuel Injection F.I. System May be Substituted for Carburetor
8 Closed-Loop Exhaust Emission Control System, Stoichiometric A/F Ratio, Optimized Ingition System	Same as 6 Above, Increased Part Load Factor Unknown, Should Make Emission Control More Difficult	Medium Risk	Low	Should be Equal to or Better than 1973 Car	Must Provide Space for Cat. Conv.	Equal Except for Converter	More Complex Control for Fuel and Electrical System But Should be Satisfactory if O_2 Sensor is Fully Developed	None	Must Develop Durable O_2 Sensor	Must Develop Controls
9 Turbocharged Spark-Ignition Engine	Emission Control Not Fully Explored To Determine NO_x Problems and Cold Start HC and CO Emissions	High Risk	Low	May Have Poor Response To Throttle	Smaller Engine Displacement by 20-30%	10% Less Engine Weight	More Complex Controls for Turbine and Fuel System	None	Spark Plug Life Not Equal to Standard	Carburetor More Complex Engine Controls & Turbocharger Must be Matched
10 Stratified Engine, Open-Chamber Type Only may Require Catalytic Converter	Cannot Meet Original 1976 Standards, Should Meet Interim 1975	High Risk for Engine Sizes Considered	Unknown Probably Fair	May not Equal Flexibility of 1973 Car	Slightly Larger	About the Same	Direct E.F.I. System is Very Complex for Open-Chamber Type	Same	Spark Plug Life May Not Equal Standard	Fuel Injection System Must be Developed to be Durable

MODIFICATIONS	COMPLIANCE WITH CONSTRAINTS	CHANCE FOR SUCCESS	GROWTH POTENTIAL	PERFORMANCE	PHYSICAL CONFIGURATIONS			EFFECT ON OTHER SUBSYSTEMS		
					SIZE	WEIGHT	COMPLEXITY	COOLING	ELECTRICAL	MECHANICAL
11 Light-weight Diesel	NO_x	Low Risk Except for Meeting Weight and Reducing Odor	Good	May have Less Performance	Slightly Larger	+20% Greater	Electrical Less Complex Fuel Injection Proven System	Less Heat Rejected to Cooling System & Exhaust System Could Result in Smaller Systems	Starter and Battery Must be Heavy-Duty Because of Higher Compression Ratio	Heavier Engine Requires Redesign of Chassis and Suspension
12 4-Speed Auto. Transmission with Optimized Shift Logic and Lockup, Torque Converter		Low Risk, Well within State of Art	Good	Excellent	Slightly Larger	Approximately 5–10% Greater	Lock-up Device More Complex	None	None	Lock-up Clutch Control Must be Improved Over 1951 Studebaker Design
13 Continuously Variable Transmission and Heavy-Duty Engine, Engine	Will Have Trouble with NO_x, 2 Gr/Mile Because of Engine Loading	High Risk Must Develop Transmission & Match to Heavy Duty Engine	Good	Excellent However, High Engine Loading Factor May Cause Slow Speed Rumble	Engine C.I.D. Smaller by 10%	Smaller C.I.D. of Engine Weight Could be Offset by Heavy-Duty Engine Requirements	Control More Complex	High Engine Loading May Change the Peak Heat Rejection Rate During the Cycle Requiring Possible Changes in Cooling System Components	None Except Spark Plug Life May be Shorter	Controls Must be Developed for Optimizing Engine Speeds and Loads t Car Speeds and Power Requirements
14 Constant-Speed Drive for Accessories without Air Conditioning	Yes	High Risk, Must Develop	Fair	None	None	None	More Complex Than VEE Belt Drive	None	None	Control More Complex
15 With Air Conditioning at one-third Duty Cycle	Yes	High Risk, Same as 14	Fair	None	None	None	More Complex Than Flex Fan	None	None	Control More Complex