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A STUDY OF TECHNOLOGICAL IMPROVEMENTS IN AUTOMOBILE FUEL CONSUMPTION
Volume II: Comprehensive Discussion

Donald A. Hurter et al

DECEMBER 1974

FINAL REPORT

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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.

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1. SUMMARY

1.1. PURPOSE

The primary objective of the work described in this report 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.

The third objective was to provide preliminary guidelines to be used by DOT/EPA in preparing plans for a possible validation test of a synthesized vehicle design recommended as a result of this study.

1.2. SCOPE AND CONDITIONS OF THE STUDY

The scope of this six-month study – (July 73 – January 74) 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 1-1).

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.

TABLE 1-1

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

1. *Automotive News* data.
2. *Automotive Industries* data.
3. *Red Book* data.
4. Compact-with PS and automatic transmission.
5. Standard-with AC, PS, PB and automatic transmission.

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 sized 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 C – General Conditions (below), if, at this point, they yielded a significant fuel consumption improvement of 3 to 5% or more.

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.

1.3. 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.

1.4 CONCLUSIONS AND RECOMMENDATIONS

1.4.1 Fuel Economy Improvements

1.4.1.1 Conclusions

1.4.1.1.1 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 (4,200 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.

1.4.1.1.2 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.

1.4.1.1.2.1 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, 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.

1.4.1.1.2.2 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.

1.4.1.1.2.3 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.

1.4.1.1.3 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.

1.4.1.2 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.

1.4.1.3 Factors to Consider in Introducing Technological Improvements

1.4.1.3.1 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.

1.4.1.3.2 Lead Time

Lead time for introducing improvements do 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).

1.4.1.3.3 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.

1.4.1.4 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.

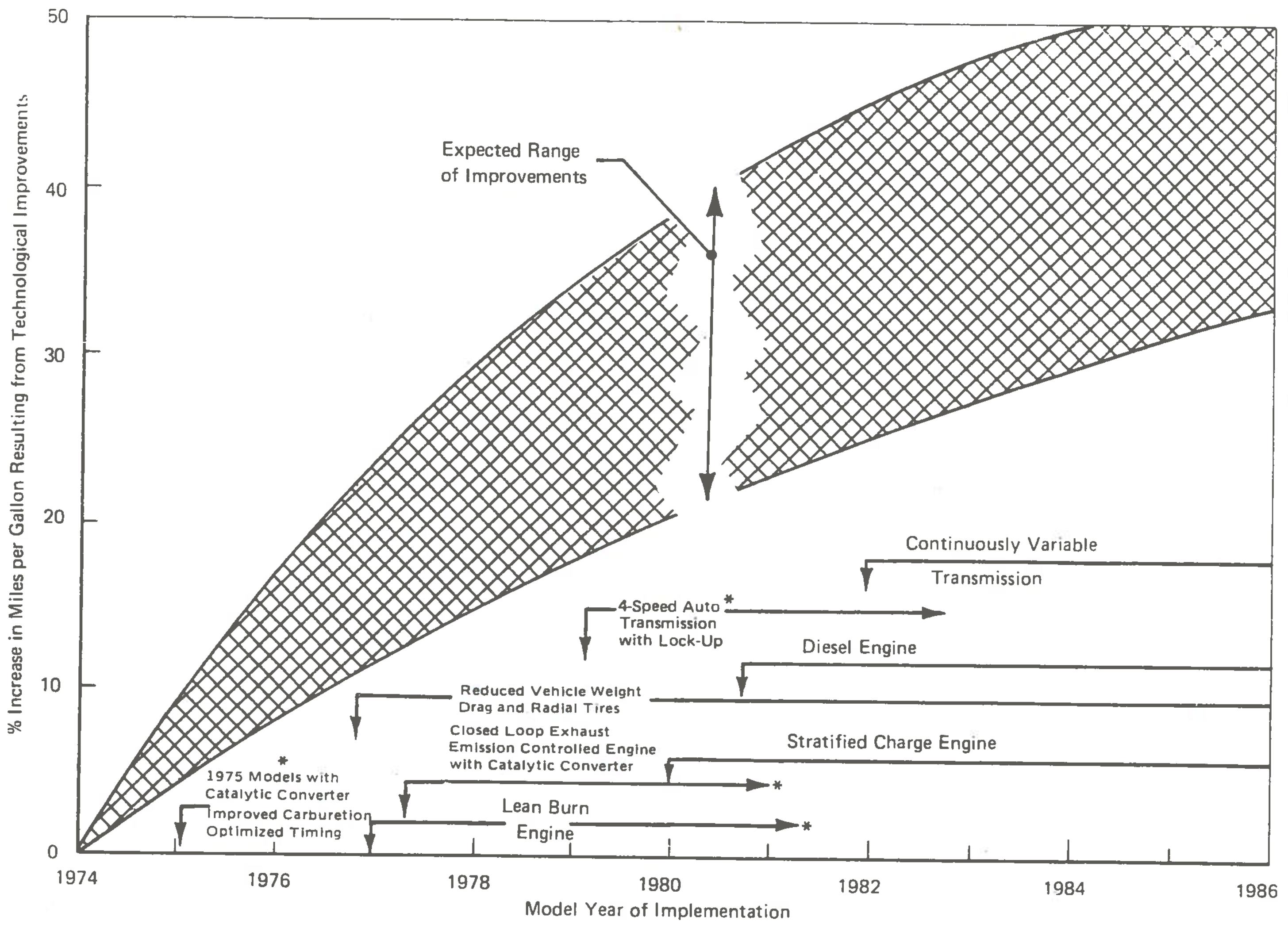
- *Medium Acceptance* – Continuously variable transmission, because of noise and engine reaction; lean burn, because of poor driveability and possible need for high octane or leaded fuels.

- *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.

1.4.1.5 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 1-1. 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 1-2 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



* 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

TABLE 1-2

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	2064	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

* 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.

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 5-2a and 5-2b).

1.4.2. Emission Constraints

1.4.2.1 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.

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.[1]

1.4.2.2 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.

1.4.3 Vehicle Fuel Economy Measurement

1.4.3.1 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

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[1] 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.

in performing fuel economy evaluations and comparison 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.

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.

1.4.3.2 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.

1.4.4. Simulation of Vehicle Fuel Economy and Performance

1.4.4.1 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.

1.4.4.2 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.

2. INTRODUCTION

2.1. BACKGROUND

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. 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 the one being documented in this report. Therefore, a review of the factors the TEP considered and conclusions reached will serve as useful background information.[2,3] The Transportation Energy Panel considered the following factors as affecting the requirements for more efficient and more diversified utilization of transportation energy:

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

2. Transportation is a major user of petroleum, 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.

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

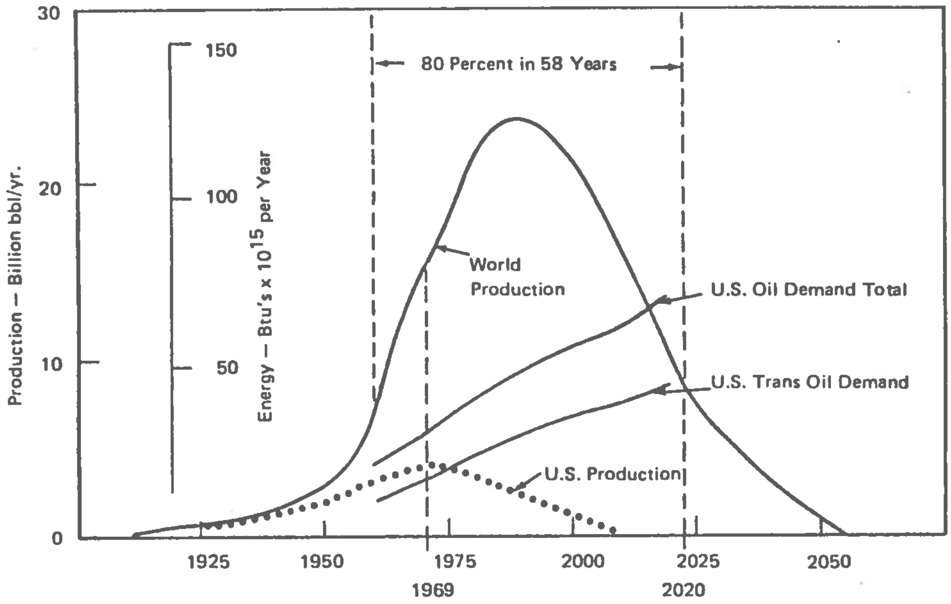
[3] Hirst, E., Energy Consumption for Transportation in the United States, ORNL-NSF-EP-15, March 1972.

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

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[4] 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,[5] 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 transportation needs might be difficult or costly to obtain to offset the petroleum requirement. Figure 2-1 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 2-1 PROJECTED WORLD OIL MARKET AND OIL PRODUCTION

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[4] Summary Technical Report of the Transportation Energy R&D Goal Panel, DOT TSC-OST-73-14, September 1972.

[5] Energy and the Automobile, SAE Paper SP-383, July 1973

In addition to the concern generated from the above factors and projections, we believe 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 current 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 cars as well with proportional gains to be expected.

2.2 APPROACH

In structuring the approach to be taken in conducting this study, we divided the total project into eight separate steps as shown in the listing at the end of this chapter. These steps, in general, were conducted in a particular sequence depending upon their interaction. Each is detailed below.

2.2.1. Step 1 — Structure Program Team

The program team was structured on the basis that the information to be handled would have to be evaluated on a technical basis, supported by information and insights obtained only from first-hand experience in the automobile industry. In addition, the very important aspects of customer acceptance ranging from assessments of comfort, appearance, cost of operation, and ease of maintenance required inputs from those associated with these concerns.

For these reasons, the Arthur D. Little (ADL), Inc., program team was augmented by consultants with expertise in automotive engines, transmissions, vehicle design, production, manufacturing, and testing, and with the automobile industry as a whole. The case team included:

Donald A. Hurter, Program Leader
John Bishop, Jr., Marketing Analysis
Raymond Carroll, Engineering Staff
W. David Lee, Engineering Staff
Harry W. Mathews, Jr., Engineering Staff
Edward R. Squibb III, Engineering Staff
John W. Stuart, Engineering Staff

The consultants working directly with the case team were:
Lawrence Hoagland, Vice President, Scientific Energy
Systems Corporation, Computer Simulation Program;

Frederick Hooven, retired Executive Engineer,
Ford Motor Company;

Max M. Roensch, retired Executive Engineer,
General Motors Corporation;

Murray Scott, Ricardo & Company Engineers (1927), Ltd.,
England

The following corporations participated throughout the project and materially assisted in providing the necessary experimental data for evaluating fuel usage in the reference vehicles, as well as providing valuable inputs for the computer modelling and simulation of fuel economy, performance, and vehicle operation. They also assisted by describing how they conducted fuel economy tests and performance measurements.

Ford Motor Company
General Motors Corporation
American Motors Corporation
Chrysler Corporation

These companies also offered their advice and comments regarding constraints, such as emission control and safety, and finally they were very helpful in providing insights on the factors that comprise user acceptance.

In addition to the automobile manufacturers we were able to obtain specific information as needed from:

Borg Warner Corporation – transmissions and air conditioning;
Bendix Corporation – electronic fuel injection systems;
Airesearch – turbocharging of engines; and
Alcoa – the use of aluminum in automobiles.

Finally, there were a number of companies that provided information about the improvements that they were developing. A complete list is included in the Appendix Section of this report.

2.2.2. Step 2 – Compliance with Constraints

The purpose of Step 2 was to measure the individual improvements and synthesized vehicle design against the federal standards for emissions and safety, evaluate potential noise restrictions, and estimate the relative effects caused by these constraints.

2.2.2.1. Step 2A – Obtain Data on the Effects of Emissions and Safety on Fuel Usage and Performance

This task was performed to determine how emission controls and safety could affect the results of an individual improvement. We found that, in many cases, the test procedures established to accumulate experimental data on an improvement did not consider the effects of emission controls, or were set at a level of emissions far more stringent than the levels set by the contract. However, every attempt was made to obtain quantitative results and to factor them into the evaluation process. When data were not available, we have so stated.

2.2.2.2. Step 2B – Using 2A, Perform Preliminary Evaluation of Individual Improvements and Later of Synthesized Vehicles for Compliance with Constraints

As a final portion of the evaluation of an individual improvement, we reviewed the constraints, tried to determine, on a judgmental level, whether the improvement should be considered further or be discarded, based on the added inputs of this factor. We used the same approach for the synthesized vehicles which resulted in the maximum possible number of choices to be considered prior to discarding because of these constraints.

2.2.3. Step 3 – Compliance with User Requirements

The purpose of Step 3 was to determine whether a given individual improvement met the user requirements as outlined by the contract, particularly in the areas of comfort, appearance, cost, ease of maintenance, reliability, durability, and repairability.

2.2.3.1. Step 3A – Prepare a List of Factors and Methods for Evaluation of User Requirements

The purpose of Step 3A was to list the factors influencing user acceptance and to use the list in discussing with the automobile manufacturers how they would evaluate the effects of these requirements. Furthermore, this list served as a means of inquiring about the reliability, durability, and repairability of individual improvements when examining an individual development. The method for evaluating costs was also developed and, where possible, cost information was gathered at the same time that the experimental data on performance were obtained. Independent assessments were made of these factors by the program team and used in evaluating the individual improvements as outlined for the evaluation of the individual improvements versus the constraints. The point was to permit the maximum number of technical improvements to be considered before discarding them because of lack of compliance with user requirements.

2.2.3.2. Step 3B – Using 3A, Perform Preliminary Evaluation of Individual Improvements and Later of Synthesized Vehicles for Compliance with Requirements

The process was repeated for each synthesized vehicle design to ascertain whether the combination of individual improvements prevented compliance with user requirements.

2.2.4. Step 4 – Select Standard and Compact Size Reference Vehicles

This step addressed itself to establishing reference vehicles for each of the automobile manufacturers for both the standard and compact size cars. The purpose of this step was to establish a benchmark against which each of the individual improvements could be measured for possible gains in fuel economy, and also to form the basis of the optimized, synthesized vehicle design.

2.2.4.1. Step 4A – Prepare Characterization and Make Selection of Standard and Compact Size Reference Vehicles

We reviewed the statistical issues of *Automotive News* and *Automotive Industries* to determine the make and model that characterized the typical mainstream vehicle sold by the manufacturers for each of the two sizes. Table 2-1, entitled Basic Data Used to Develop Composite Reference Vehicle (1973) for Compact and Standard Passenger Vehicles, displays the specific details on each of the makes and models selected. The variation in the characteristics and specifications of these models indicates that the compact (intermediate) weight vehicle, which includes all American manufacturers, is a four-door sedan weighing from 2,800 to 3,300 pounds, with a wheelbase of 108 to 111 inches, powered by a six-cylinder, 225 to 250 cubic inch engine with a horsepower ranging from 88 to 105, equipped with power steering, but not having air conditioning, and sold in volumes ranging from 250,000 to 300,000 units per manufacturer per year for the 1973 model.

The standard (heavy) weight composite vehicle is considered to be a two-door hardtop model ranging in weight from 4,000 to 4,500 pounds with a wheelbase of 120 to 121.5 inches powered by a 350 to 400 cubic inch V-8 cylinder engine with horsepower ranging from 145 to 170. Standard equipment included automatic transmission, power steering and brakes, and optional air conditioning, and sold in volumes ranging from 280,000 to 540,000 units per year.

2.2.4.2. Step 4B – Interface with U.S. Auto Manufacturers to Obtain Data

Using the description of the composite standard size and compact size automobiles, we contacted each of the American automobile manufacturers and asked them to supply us with data on their model which most nearly matched the composite car specification. We agreed to keep the information supplied confidential, coding any reference to it to prevent identification with a specific make or model.

The format we used to select the information is also included in the Appendix Section. It embraced five categories:

1. The specifications of the model which most nearly represented the composite vehicle specifications, that is, body style, options, shipping weight, wheelbase, axle ratio, engine size, transmission, and the like.
2. Fuel consumption data based on actual measurement for various steady-state conditions and, if possible, the federal driving cycle.
3. Fuel consumption data during cold idle, hot idle, and cold start.
4. Power used by the auxiliaries and accessories for various engine speeds and horsepower.
5. Specific performance characteristics, such as acceleration from 0 to 60 mph, and passing maneuvers as specified by federal regulations.

We held discussions with each of the manufacturers to determine how they conducted their tests and what consideration they felt would have to be given to standardized data to make possible meaningful comparisons.

Since most of the information gleaned from manufacturers and suppliers was of a sensitive nature, we agreed to make every effort possible to prevent its misuse. Therefore, where necessary, we coded all the experimental data to prevent identifying the information with a particular make or model automobile.

2.2.4.3. Step 4C – Determine from Data Obtained and Computer Program Analysis How Power is Used in Vehicles

Using the data obtained from the manufacturers, we conducted separate studies to determine how power would be used in the composite reference vehicle. The results of this phase of our study are discussed in Chapter IV-B entitled, "Fuel Usage of the Reference Vehicles."

2.2.4.4. Step 4D – Evaluate Possibilities for Making Significant Improvements in Fuel Usage

Having determined how the power is used in operating the vehicle, we identified for future study possible areas in which significant improvements might be realized.

2.2.5. Step 5 – Develop Fuel Economy and Performance Measurement Techniques

The purpose of this task was to develop a fuel economy measurement technique, so that relative improvements could be measured and total annual fuel savings could be estimated.

2.2.5.1. Step 5A – Obtain Information, Procedures, and Data on Testing Techniques, from EPA, DOT, Auto Manufacturers, and Others

During the course of obtaining information on the reference vehicles, we solicited information regarding test procedures, testing techniques, and actual recommendations for measuring fuel economy from the automobile manufacturers, the EPA, the Department of Transportation, and other sources, as applicable.

2.2.5.2 Step 5B – Determine Other Influencing Factors Which Affect Fuel Usage and Performance

At the same time, we conducted Step 5B to determine other influencing factors which affect fuel economy and performance, such as cold start versus hot start, ambient conditions, driving styles, etc.

2.2.5.3 Step 5C – Perform a Statistical Evaluation of Published Driving Modes and Develop a Simple Rationale for Assessing Tank Mileage

Having obtained pertinent information in Steps 5A and 5B, we then performed a statistical evaluation of published driving modes with the objective of developing a simple rationale for assessing tank mileage. This work is included in Chapter IV – Fuel Economy, in Section A, Measurement Techniques.

2.2.6. Step 6 – Identify and Evaluate Technological Improvements

The purpose of this step was to identify and evaluate the technological improvements which could contribute to a reduction in fuel usage when incorporated into an optimized vehicle design.

2.2.6.1. Step 6A – Prepare Preliminary List of Obvious Technological Improvements

At the very beginning of our study, we generated a list of technical improvements which we felt could be incorporated in an automobile design which would meet the conditions set forth in the Statement of Work.

2.2.6.2/3. Steps 6B and 6C – Identify Parties Developing Improvements and Obtain Data

Having completed the list in Step 6A, we proceeded to identify those partners and organizations actively engaged in developing these improvements and to solicit pertinent data we might use in our analysis. This particular undertaking involved interviews and field trips to the developers' sites both to obtain the information as well as ascertain by first-hand observation just how far these developers had progressed. On some occasions return trips were necessary as described in Step 6E.

2.2.6.4 Step 6D – Screen All Individual Improvements Against Constraints and Conditions of Programs, i.e., Federal Constraints, User Requirements, Effect on Vehicle System, Time Frame of Acceptance

The list of individual technological improvements was next screened and evaluated against constraints and conditions of the program. The screening of each improvement against various constraints and requirements was a continuing process throughout the study with the principal influence on actual fuel economy improvement and possible degradation of performance. In many cases we found that when the data were examined there was only a marginal fuel economy improvement possible and that performance was frequently impaired.

The available data were then collected and reviewed carefully for use in the computer simulation program. Wherever possible, we collected data on fuel consumption and emission results on a comparable basis. However, the innovators did not always provide such information on an equal basis. Therefore, in such cases, we used our best judgment in extrapolating the data made available.

2.2.6.5 Step 6E – Conduct Field Trips to Evaluate State of Development of Improvements and Acceptability to User

Where at all possible, we attempted to observe the performance of any vehicle in which an individual improvement was incorporated to ascertain how the vehicle performed and to assess the general state of the development of the improvement. In some cases this was the only manner in which actual data were obtained pertaining to the driveability of the car.

2.2.6.6. Step 6F – Determine Final Selection of Individual Improvements for Incorporation into Optimum Synthesized Vehicle

The purpose of this step was to determine the final selection of individual improvements for incorporation into an optimized, synthesized vehicle. We used the inputs from a variety of sources to screen the individual improvements and, on a judgment basis, considered only those that seemed practical for incorporation into a total system.

2.2.6.7 Step 6G – Interface Improvements for Combining into Optimized Synthesized Vehicle

In Step 6G we interfaced the improvements for mutual component acceptability. At this point we were able to describe each vehicle possibility. Our next step in time sequence was Step 7D, the Simulation of the Various Combinations of Synthesized Vehicles for Total Improvement to Measure Fuel Economy and Performance. We used the computer program to evaluate fuel economy and performance. The results are presented in Chapter V.

2.2.7. Step 7 – Analytical Simulation of Fuel Economy and Performance

The purpose of this step was to develop the analytical tools for predicting fuel usage and vehicle performance for the reference vehicles, improvements and optimized vehicle design. This was accomplished by a number of methods and techniques, the principal one being a computer modelling program for predicting fuel usage.

2.2.7.1. Step 7A – Modify Existing Analytical Program for Simulation of Vehicle Operation to Obtain Results on Fuel Usage and Performance

At the beginning of this study, the Scientific Energy Systems Corporation, acting as consultants to ADL, proceeded to modify an existing computer program used to simulate vehicle operation to obtain results on fuel economy and performance on: (a) the reference vehicles, (b) the reference vehicles with individual improvements, and (c) the optimized, synthesized design vehicles. The description of this program and typical outputs are included in the Appendix Section.

2.2.7.2. Step 7B – Determine Necessary Input Data and Proper Format for Obtaining Data in 4B and 6B

Concurrent with modifying the existing computer program at SES, we established the necessary input information and proper format for this information and generated descriptions. We then used this format to obtain data on improvements from both developers and automobile manufacturers.

2.2.7.3. Step 7C – Conduct Analytical Simulation Operation of Reference Vehicles and Measure Results against Experimental Data to Verify Acceptability

To verify SES's computer modeling simulation program we fed the data received for the reference vehicles into the computer to acquire fuel economy predictions for various steady-state conditions and the federal driving cycle. We then compared these results with the experimental data provided for the reference vehicles and the results obtained from a similar computer simulation program, and resolved the differences between the results. See Appendix V, Section 2.2.3, pages 209 – 210a for details of the simulation program and verification.

2.2.7.4. Step 7D – Simulate the Operations of Reference Vehicles Using Each Individual Improvement to Predict Fuel Usage and Performance Rank Results

We next added each individual improvement to the composite reference vehicle data and predicted the fuel economy and performance results. This process continued as information was obtained from sources outlined in Steps 6B, 6C, and 6D.

2.2.7.5. Step 7E – Simulate the Various Combinations of Synthesized Vehicles to Determine Total Improvements in Fuel Economy and Performance

The purpose of this step was to combine the individual improvements which, in the opinion of the case team, represented a realistic vehicle design for further study, recognizing that each of the individual improvements had been screened carefully as described in Steps 2, 3, 6 and 7.

2.2.8. Step 8 – Design Assessment of Optimized Synthesized Standard and Compact Size Vehicles

Having determined the possible fuel economy and performance for each synthesized vehicle in the standard and compact size automobiles, we then performed a complete assessment and evaluation of each of the synthesized vehicle designs as developed under the preceding tasks.

2.2.8.1. Step 8A – Perform a Total System Evaluation for each Synthesized Vehicle Selected

In this step, we evaluated fuel economy, performance, technical compatibility, compliance with constraints, user acceptability, and adaptability to reference vehicles. This task was conducted

STEP-BY-STEP APPROACH TO FUEL ECONOMY STUDY

Step 1 Structure Program Team

Step 2 Determine Compliance with Constraints
2A Obtain Data on the Effects of Emissions and Safety on Fuel Usage and Performance
2B Using 2A, Perform Preliminary Evaluation of Individual Improvements and Later of Synthesized Vehicles for Compliance with Constraints

Step 3 Determine Compliance with User Requirements
3A Prepare a List of Factors and Methods for Evaluation of User Requirements
3B Using 3A, Perform Preliminary Evaluation of Individual Improvements and Later of Synthesized Vehicles for Compliance with Requirements

Step 4 Select Standard and Compact Size Reference Vehicles
4A Prepare Characterization and Make Selection of Standard and Compact Size Reference Vehicles
4B Interface with U.S. Auto Manufacturers to Obtain Data
4C Determine from Data Obtained and Computer Program Analysis How Power is Used in Vehicles
4D Evaluate Possibilities for Making Significant Improvements in Fuel Usage

Step 5 Develop Economy and Performance Measurement Techniques
5A Obtain Information, Procedures, and Data on Testing Techniques from EPA, DOT, Auto Manufacturers, and Others
5B Determine Other Influencing Factors which Affect Fuel Usage and Performance
5C Perform a Statistical Evaluation of Published Driving Modes and Develop a Simple Rationale for Assessing Tank Mileage

Step 6 Identify and Evaluate Technological Improvements
6A Prepare Preliminary List of Obvious Technological Improvements
6B Identify Parties Developing Improvements and Obtain Their Data
6C Add Results of 4D to Preliminary List of Improvements, Identify Developer, and Obtain Data for Analysis of Computer Simulation
6D Screen All Individual Improvements against Constraints and Conditions of Programs, i.e., Federal Constraints, User Requirements, Effect on Vehicle System, Time Frame of Acceptance
6E Conduct Field Trips to Evaluate State of Development of Improvements and Acceptability to User
6F Determine Final Selection of Individual Improvements for Incorporation into Optimum Synthesized Vehicle
6G Interface Improvements for Combining into Optimized Synthesized Vehicle

Step 7 Analytical Simulation of Fuel Economy and Performance
7A Modify Existing Analytical Program for Simulation of Vehicle Operation to Obtain Results on Fuel Usage and Performance
7B Determine Necessary Input Data and Proper Format for Computer
7C Conduct Analytical Simulation Operation of Reference Vehicles and Measure Results against Experimental Data to Verify Acceptability
7D Simulate the Operations of Reference Vehicles Using Each Individual Improvement to Predict Fuel Usage and Performance Rank

STEP-BY-STEP APPROACH TO FUEL ECONOMY STUDY

Step 7E Simulate the Various Combinations of Synthesized Vehicles to Determine Total Improvements in Fuel Economy and Performance

Step 8 Perform Design Assessment of Optimized Synthesized Standard and Compact Size Vehicles

- 8A Perform a Total System Evaluation for Each Synthesized Vehicle Selected
- 8B Rank Synthesized Vehicles Designs against One Another in Accordance with Program Goals
- 8C Draw Conclusions and Recommendations on Designs and Prepare Appropriate Preliminary Program Plans for Selected Synthesized Vehicles

3. FUEL ECONOMY VERSUS GOVERNMENTAL CONSTRAINTS, OPERATING CONDITIONS, AND USER/MARKET REQUIREMENTS

3.1. INTRODUCTION

The purpose of this section is to provide background information on how automobile fuel economy has changed in the past 10 years and to examine the influencing factors which have adversely affected fuel economy. Many factors influence fuel economy and, for purposes of this report, we have tried to group them into two categories: (1) internal factors relating to how the vehicle was designed and constructed to meet the requirements set by (2) the external factors, conditions, and constraints arising from user requirements, operating conditions, and in recent years those set by the Government.

In this chapter we will examine those external factors to determine how they affect fuel economy. In the following chapters we will examine the internal factors of vehicle design and construction to determine what action can be taken to offset the external factors and improve fuel economy.

The current energy crisis has made everyone aware of the deterioration of fuel economy, particularly in relation to the larger 1973 and 1974 model cars. Although not generally known, a great deal of attention has been given heretofore to fuel economy by the automobile industry and the Government as attested to by the many studies completed on the subject (see Bibliography).

We have not become involved in the similarities and differences of the results of these studies, but have accepted their overall conclusion that new standard and compact cars today use more fuel than those built during the early and mid 1960's. Table 3-1 (developed from information in Reference 6) shows the adverse changes in fuel economy and performance from the mid 1960's to the present day.[6] In the fuel economy comparison, we used a 1965 standard size, four-door sedan with optional small V-8 engine, automatic transmission, power steering, and power brakes. By 1971 this car had included air conditioning which, while not standard, is now being installed in about 85% of the vehicles of this size.

We chose 1965 as a starting point because powerplants, transmissions, and body designs had reached a high degree of efficiency by then and, secondly, because in these models there were no emission control devices which exact an appreciable toll on fuel consumption.

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6. MacDonald, H.C., Consumption Trends in Today's Vehicles, Paper I-I-A (12), SAE 730517, July 1973.

TABLE 3-1

FACTORS INFLUENCING STANDARD-SIZE CAR FUEL ECONOMY, WEIGHT AND PERFORMANCE

Year	Governmental Automobile Exhaust Emission Standards (grams per mile)			User/Market Trend Requirements Approximate % Standard Cars Sold with Following Options			Engine Size (cu. in. displacement)	Weight Changed (lb)	Fuel Economy		Performance % of 1965 Car
	HC	CO	NOX	Air Conditioning	Power Steering	Automatic Transmission			(mpg)	(%)	
1965	(8.5)*	(98)*	(3.4)*	40	73	85	289	3550	15	100	100
1968	(6.3)*	(79.0)*	(4.2)*	45	77	89	300	3750	14.5	97	92
1971	4.6	47.0	N.R.	61	79	90	350+	4150	13	85	92
1973	3.4	39.0	3.0	85	85	92	400+	4275**	12	79	88
1975	1.5	15.0	3.1	85	85	92	400+	5000**	11.1	74	82

*Numbers in parentheses are not standards, but are estimates of average emission levels, in grams per mile had the C.V.S. 72 test procedure been used.

**Additional weight attributed in part to safety and damageability requirements.

+Engine size increased to maintain performance.

N.R. — Not required by government but California standards are 4 GPM.

In Table 3-1, using the same baseline automobile, we have attempted to show how a number of external factors influencing fuel economy have appeared or increased since 1965. Of course, it is difficult to ascribe the drop in fuel economy and performance directly to any one factor or combination of factors. However, our opinion, along with many others, is that the major loss in fuel economy is due first to the manner in which the manufacturer chose to meet standards with the prescribed use of emission control devices and, secondly, to the increase in automobile weight.[7,8] Conversely, we feel that the loss in acceleration is first due to the weight increase and, second, due to the emission control devices. However, making the engine larger and adjusting the axle ratio to regain lost performance would have a very adverse effect on fuel economy.

In our evaluation of individual improvements and synthesized designs, we have considered all of these factors, particularly where an improvement concept differs considerably from current practice.

In the following section, we have defined the certain factors, such as emission controls, safety, and the like, and suggested a method to be used in considering the factors when evaluating the individual concept or synthesized vehicle.

3.2. GOVERNMENTAL CONSTRAINTS

3.2.1. Emission Controls

Table 3-1 displays the various levels of emissions permitted and the year they became effective. For the purpose of this study and in anticipation of a relaxation in the NO_x standard, the amount for the NO_x was changed from 0.4 to 2.0 gm/mile.

We have examined all concepts with these standards as goals and found that the developers of improvements universally were very conscious of these requirements. In fact, in many cases they were working toward meeting the tightened NO_x standard of 0.4 gm/mile. Therefore, we were able to obtain test data that included results showing whether compliance had been met or not. In the case of data that did not include this information we used our best judgment and have documented this study accordingly.

As is generally recognized, NO_x is the most difficult pollutant to control at the levels required while monitoring fuel economy. Approaches which lower peak combustion chamber temperature and exposure time needed to control NO_x also reduce the efficiency of the engine and increase fuel consumption. Conversely, improvements which effectively overcome the inefficient operation in a spark-ignited engine, e.g., part load-part throttle, usually tend to produce more NO_x. However, quite recently work performed by the engineering staff of General Motors[8] indicates that by proper proportioning of E.G.R. to engine load fuel economy maybe regained.

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7. Huebner, Jr., G.J., and Gasser, D.F., General Factors Affecting Vehicle Fuel Consumption, SAE 730518, July 1973.
8. Gumbleton, J.J., Bolton, R.A., and Lang, H.W., Optimizing Engine Parameters with Exhaust Gas Recirculation, SAE Paper 74014, Feb. 25-March 1, 1974.

The problem presented by these opposing situations was also considered in our evaluations.

3.2.2. Safety and Damageability

The standards for safety and damageability were agreed to be equal to or better than those represented by the 1973 reference vehicles. We feel that the only significant improvement which would be materially affected by these constraints is that of weight reduction either by substitution of lighter materials or redesign for weight reduction using original materials. Therefore, we were quite conservative in our estimate of how much the reference vehicles could be reduced in weight and set a 10% weight reduction as a maximum. This was confirmed by discussion with the industry.

There were isolated cases* in which safety practices other than those related to crash protection were identified and investigated on an individual engineering basis, e.g., the use of hydrogen fuel.

3.2.3. Noise

At present no federal standards relating to noise have been set. However, any improvement which had the potential of creating a bothersome noise level (pitch frequency, etc.) different from those of the reference vehicle was evaluated and documented. The characteristic diesel knock and potential whine of a constant high-speed drive are examples of the noise type of concern.

3.2.4. Fuel Octane Level

In this study we assumed that all gasoline Spark Ignition engine concepts considered would use research octane number (RON) 91 fuel with the exception of the lean burn engine (Section 4.3.3.2) which might incorporate compression ratios necessitating higher than RON 91 fuels.

3.3 OPERATIONAL CONDITIONS, DEFINITIONS, AND EFFECTS

In this section we will cover those constraints which follow from meeting the operational requirements of the vehicle as set by external physical conditions and factors. Generally, these operational requirements may be modified to some extent by the user, but lie beyond his ability to influence under all situations. Examples include ambient temperature, road grade, traffic, road speed, frequency of idling, and all operational requirements.

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* For instance, we considered the use of hydrogen fuel to be impractical at the present time for a number of reasons, one of which was related to the safety aspects of storing and transporting hydrogen in a passenger automobile.

These conditions have a marked effect on fuel usage and, unless care is taken in dealing with them, a serious misunderstanding of a vehicle's fuel usage and to what degree an improvement has been made may follow. However, we have tried to simplify the method used to evaluate an improvement by fixing and holding constant many of the conditions described in this section. Then, after the evaluation, we determined where improvements in fuel usage had been made on each improvement, where possible, and the effect of the various conditions.

In the following subsections we discuss these conditions and their possible effects on vehicle fuel economy.

3.3.1. Operating Requirements

3.3.1.1. Acceleration

Performance is the term generally used to describe the ability to accelerate. In evaluating improvements, we took care to note that the vehicle incorporating the improvement could still accelerate at a rate within ± 10% of the reference vehicle. The primary acceleration comparisons were made by determining elapsed time for the following:

0–30 mph
0–60 mph
50–70 mph

Each vehicle was also examined to determine its compliance with the federal requirement for an emergency duty passing maneuver.

We took great care to adjust engine size, power-to-weight ratios, and drive train gear ratios to satisfy the condition of equal performance before we compared the final fuel usage results of the "improved" vehicle and the reference vehicle. Many times in the past those announcing fuel improvements have failed to mention concomitant degradation of performance.

Although we had adjusted the vehicles to accelerate at the same rate and then analyzed them under the same driving conditions, there was still one other factor which had to be considered – driver habits. In a series of controlled tests in which the test vehicles were run at both double and one-half the normal acceleration and deceleration rates specified by General Motors for city fuel economy, Scheffler and Niepoth[9] verified the fuel savings possible when moderate driving practices are adopted. Their tests proved that the "Sunday" driver could expect to save a gallon of gasoline over the normal driver, while the "hot rod" driver could expect to pay a penalty of one mile per gallon when compared to the driver accelerating and decelerating normally (Figure 3-1).

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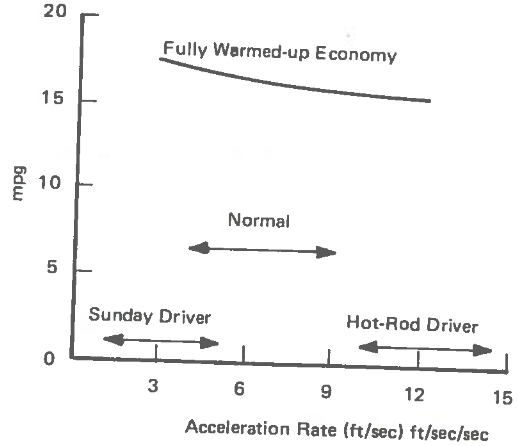
[9] Scheffler, C.E., and Niepoth, G.W., Customer Fuel Economy Estimated from Engineering Tests, SAE 650861, 1965.



Note: City fuel economy values were first run with normal acceleration and deceleration rates, and then were repeated with these rates first halved and then doubled. Fully warmed-up economy was reduced by greater acceleration and deceleration rates.

Source: SAE 710137, 1971

FIGURE 3–1 DRIVER HABITS

3.3.1.2. Driveability and Transient Response

Driveability is a term which describes how dependably and smoothly a car's power train operates under all kinds of weather and operating conditions. However, it does not include ride and handling quality, braking performance, or an abnormal combustion phenomenon such as knock. While the user considers driveability one of many requirements that has to be satisfied, we have considered it to be a very necessary requirement from a safety or operation standpoint. Similar to the performance evaluation, no appreciable change in driveability was considered permissible while evaluating improvements; for instance, concepts which rely on a lean fuel/air ratio mixture or the stratified charge engine usually degrade driveability.

Since the driveability attribute was considered so important, every attempt was made to evaluate improvements by field-testing if we judged that they would degrade the driveability. In our judgment driveability cannot be simulated. However, R.L. Everett has described how tests have been developed to quantify objectively certain aspects of driveability.[10] Everett's paper presents a comprehensive list of factors related to evaluating driveability. We considered most of the categories listed under the cold start and driveaway tests to be of prime importance from a safety-of-operation standpoint, and these factors should be measured carefully during any validation testing of vehicle concepts.

We believe that various areas that must be considered when evaluating driveability may be categorized into divisions: (1) those which are of prime importance from a safety-of-operation standpoint, and (2) those that are judged by the customer in accepting the vehicle for his use. Poor driveability is generally caused by poor fuel management. This may come about from a variety of causes, including fuel distribution in manifolding, value overlap, and poor carburetion at certain engine speeds. In addition, the engine and transmission may be poorly matched causing the engine to operate momentarily in a region of unstable operation.

We have attempted to identify if an individual concept would inherently be likely to cause a problem in driveability without examining the detailed causes.

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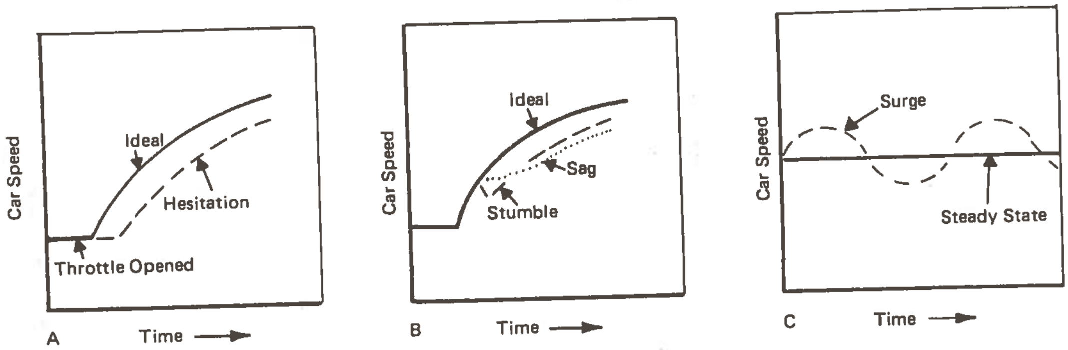
[10] Everett, R.L., Measuring Vehicle Driveability, SAE 710137, 1971.

The following is a listing and definition of driveability problems affecting safety:

1. *Stall after Start* – The engine stalls immediately after starting or upon lowering the idle speed by releasing the fast idle cam prior to driving away.

2. *Hesitation* – A lack of response to initial throttle opening, occurring when driving away from a standstill or accelerating from any speed. Hesitation is illustrated in Figure 3-2. Ideally, acceleration occurs immediately when the throttle is opened. The horizontal dashed line in Figure 3-2A indicates a delay in response or "hesitation."



Note: Graphical description of driveability terms: A-hesitation; B-sag or stumble.

Source: SAE 710137, Jan. 1971

FIGURE 3–2 ADDITIONAL DRIVEABILITY FEATURES CONSIDERED IMPORTANT BY CUSTOMERS

3. *Sag or Stumble* – A noticeable loss of power, similar to hesitation, occurs during an acceleration, except that it occurs after the car is accelerating. The purists define stumble as a sudden loss of power (similar to ignition failure), while sag is a less severe loss of power. Sag and stumble are illustrated in Figure 3-2B.

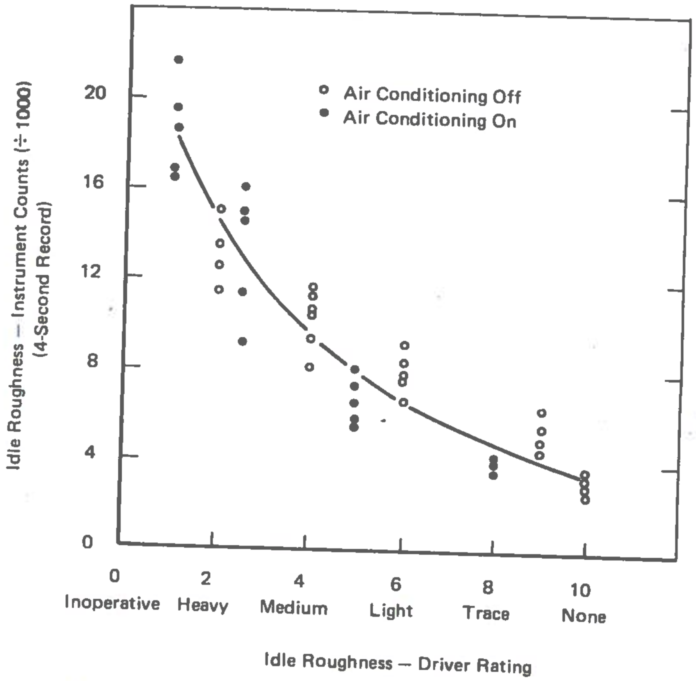
4. *Stall While Moving or Attempting to Move* – The engine stalls as the driver attempts to put his car in motion or while the car is in motion. Moving stalls occur most frequently when an attempt is made to accelerate before an engine has been warmed up.

5. *Surge* – Defined as a low-frequency (less than 10 cps) fore and aft oscillation of the vehicle while cruising or accelerating at part throttle. It is generally associated with lean air/fuel ratio carburetion (see Figure 3-2C). A surgemeter has been developed for measuring vehicle surge. Instrument-driver comparisons indicate the instrument can measure surge objectively. Two applications of the surgemeter showed that vehicle surge increased when the amount of exhaust gas recirculation required for oxides of nitrogen control was

increased, and there were differences in surge levels in seven 1970 model cars. Also, cold-start and driveaway tests on the same seven cars indicated differences in driveability performance.

6. *Stretchiness* – This term describes a lack of performance during light to moderate accelerations. Stretchiness, like surge, is associated with lean carburetion, but is not necessarily accompanied by surge. Stretchiness can be evaluated on different cars by comparing the acceleration rates at specific intake manifold vacuums. For example, if one car accelerates from 30 to 60 mph in 25 seconds with a 10 in. Hg intake manifold vacuum, and a second car, of the same make as the first, takes 35 seconds, the second car would be considered more stretchy than the first. The major problem in trying to measure stretchiness in absolute terms is establishing a base line acceleration rate, since power-to-weight ratio, axle ratio, and transmission characteristics all affect performance.

7. *Idle Roughness Measurement* – Experiments have been run to determine if surgemeters could be used to measure idle quality. Instrumentation is available for surge rating tests. The idle quality of the test vehicle is varied by adjusting the idle mixture screws and air flow. Measurements, usually of 4-second duration, are made at each idle setting, with air conditioning on and off. When appropriate, driver's ratings are the same at each idle setting. Surgemeters appear sensitive enough to detect differences in idle quality. However, more test work is required to determine the practicality of measuring idle quality. An example of plotted data is shown in Figure 3-3.



Source: SAE 710137, Jan. 1971

FIGURE 3–3 IDLE QUALITY – DRIVER VERSUS INSTRUMENT

We should restate that all of the above driveability factors are considered to be very important in the evaluation of an improvement and that, whenever possible, field trials of vehicles were made to determine on a qualitative basis how these factors were affected by the improvement. No attempt was made to perform an analytical simulation or quantitative measurement of these factors. This would be necessary in any future validation test.

The point to be stressed is that any evaluation of a performance improvement should not be totally evaluated by simulation alone, but must be physically tested under all expected operating conditions to determine the qualitative aspects.

3.3.2. Road Load and Grade Considerations

3.3.2.1. Driving Modes

All analytical simulations performed during this study were based on the federal driving cycle plus constant-speed values of 30, 40, 50, 60, 70 mph on a level road with an average highway road surface.

3.3.2.2. Cruise or Road Load

Cruise or road load driving is done at constant speed and constant throttle on a level road. In evaluating the reference vehicles and synthesized design vehicles, we did not consider the effect of grade on fuel economy for the constant-speed, road load conditions.

3.3.2.3. Grade

In calculating the yearly fuel consumption we did not consider the effect of grade. Figure 3-4 illustrates the change in fuel economy for a typical standard size car for -4% to +4% grades at speeds from 20 to 80 mph as summarized from various published documents. The figure shows how road grade affects fuel economy.

3.3.3. Hot and Cold Starts

In commenting on hot and cold starts, we first define our terms:

1. *Cold Start* – Starting a cold engine, that is, an engine that has reached equilibrium with the ambient temperature.

2. *Hot Start* – Starting a warm engine – an engine whose temperature is significantly higher than ambient.

3. *Time to Start* – The number of seconds required to start an engine, usually measured by the time the ignition key is in the start position.

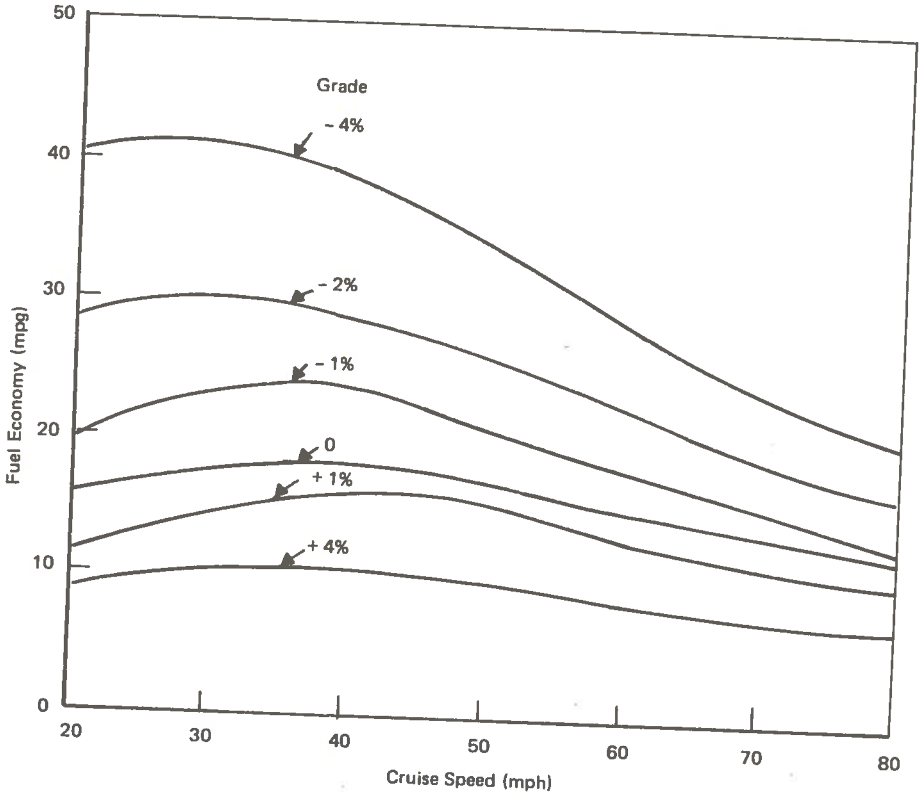


FIGURE 3–4 ESTIMATED EFFECT OF GRADES ON FUEL ECONOMY FOR A TYPICAL STANDARD-SIZE VEHICLE

In evaluating fuel economy, careful consideration must be given to hot start versus cold start as each of these conditions affects fuel economy. For example, a vehicle driven a distance of 10 miles at the same ambient temperature can have a fuel economy difference of as much as 3 to 5 mpg[11] using General Motors Business District Driving Cycle, depending on whether its initial startup was hot or cold. Figure 3-5 presents an example of these effects, illustrating the results of an extensive test series used to determine the cumulative effect on fuel economy of a vehicle driven in city conditions at an ambient temperature of 10°F with the vehicle in a cold start condition.

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[11] Scheffler, C.E., and Niepoth, G.W., Customer Fuel Economy Estimated from Engineering Tests, Paper IV-1 (10), SAE 650861, 1965.

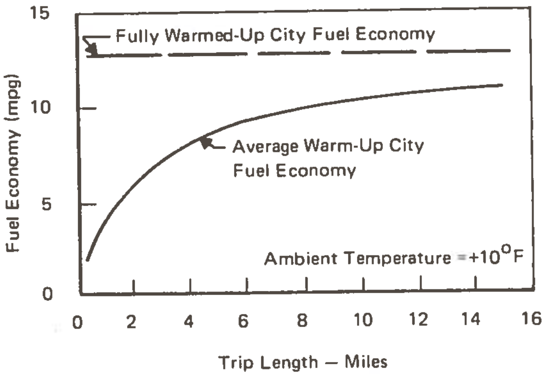
TABLE 3-2

AUTO TRIP STATISTICS – URBAN MILEAGE

Trip Length (One-Way Miles)	Trips (%)	Vehicle Miles (%)
Under 5	54.1	11.1
5- 9	19.6	13.8
10-15	13.8	18.7
16-20	4.3	9.1
21-30	4.0	11.8
31-40	1.6	6.6
41-50	0.8	4.3
51-99	1.0	7.6
100 and over	0.8	17.0
Total	100.0	100.0

Total Mileage

Urban	55.5%
Highway	44.5%



Source: SAE 650861, 1965

FIGURE 3–5 AVERAGE FUEL ECONOMY IN CITY DRIVING AT 10°F BEGINNING WITH A COLD START

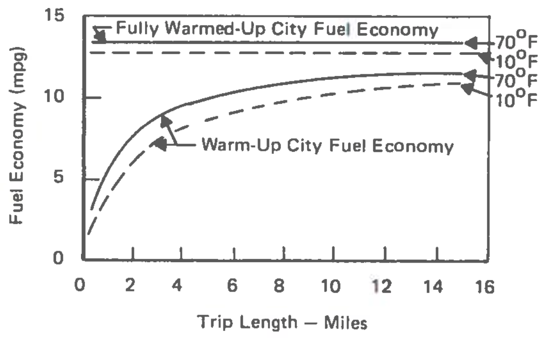
The majority of day-to-day driving consists of a series of short trips and includes some vehicle warmup each time the car is driven. Data compiled by the Motor Vehicles Manufacturers Association indicates that approximately 55% of passenger car trips are no longer than 5 miles, 20% are between 5 and 10 miles, 18% are between 10 and 20 miles, and 7% are greater than 20 miles. Table 3-2 shows the relationship between "percent trips" versus "percent vehicle miles" travelled.

Figure 3-5 also dramatically illustrates the relative difference in fuel economy for short trips. For a cold start, the average fuel economy level for a 2-mile trip is 6 mpg. For a cold start trip of 10 miles the average fuel economy level is 10 mpg. This illustrates the maximum improvement possible between running a cold engine versus a fully warmed engine for short trips, that is, 15 miles or less. Although these gains are indicative, no practical method is currently available to keep the engine and drive train components at their normal operating temperatures during the non-operational period. However, storing in a heated garage or using engine block heaters allows partial gains in cold start fuel economy.

However, we recognize that most cars are not kept in heated garages either away or at one's place of residence, and that current motivation or habits of users and the current vehicle equipment does not of itself encourage widespread use of engine block heating. Therefore, we have not included this technique as a fuel economy gain.

The major cause for this extra fuel consumption is due to high frictional losses of engine and drive train components; next is higher lubricant viscosity which creates additional friction losses, and finally the use of energy to bring the engine and vehicle up to operating temperature.

The effect of choke action has been thought to be a major factor in fuel consumption. Figure 3-6 illustrates the difference between operating with choke open (fully warmed up) and choke closed and then slowly opening after cold start. This accounts for an average difference of only 1 mpg. However, the figure shows that the major loss is not due to this factor, but that the losses during vehicle warmup were large, regardless of choke action.



Note: In the summer a car warms up a little faster, and gets better mileage. However, cumulative mpg curves during warm-up were similar at the two different temperatures. The summer temperature minimized choke action, but still there were large mpg losses during vehicle warm-up.

Source: SAE 680861, 1965

FIGURE 3–6 WARM-UP ECONOMY

Choke action does affect emissions of CO and HC markedly. Therefore, much effort has been made to hasten the opening of the choke, which, of course, also improves fuel economy.

Evaluations of the individual improvement and synthesized vehicle designs were all based on fully warmed up conditions, and we did not consider the effects of cold starts because quantitative data on cold startup were not available for use in this study. Where, in our judgment, a concept improved the cold start fuel economy, we identified the effects and drew a conclusion.

3.3.4. Ambient Conditions

Weather and altitude are important factors in determining fuel economy and in assessing the driveability of a vehicle. The primary weather factors which have to be considered are described below.

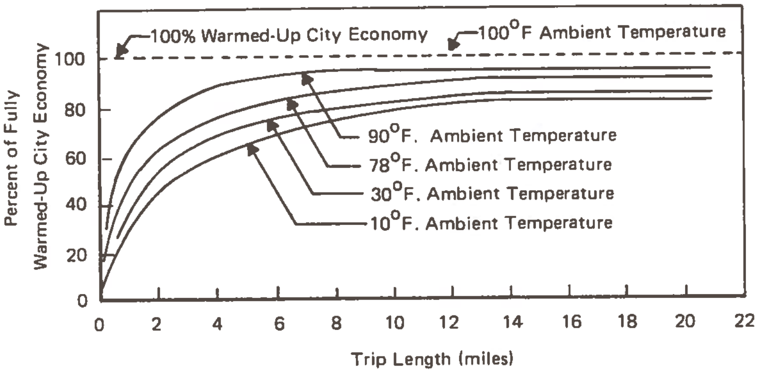
3.3.4.1. Temperature

The effect of temperature on gasoline vapor formation ranks as the most important atmospheric variable which has to be considered in driveability testing. If too little vapor is provided during cold starting or cold driveaway, long starting times or poor warmup performance tend to result. An excess of fuel vapor in hot weather, on the other hand, can cause vapor lock and difficulties in starting.

Temperature-control devices are used in many cars today to maintain satisfactory idle performance, or to improve engine cooling at high temperatures. The operation of these devices has to be considered in any performance assessment.

Engine mixture ratios can also be affected by temperature variations, because carburetion is unable to compensate for the changes in mass air flow caused by variations in the air temperature. This problem has been minimized on many later models by use of a heated inlet air system which results in minimization of the variations in the temperature of the inlet air.

Although most passenger car miles are accumulated during short trips during which cold starting conditions exist, the effect of ambient temperature on fully warmed-up city fuel economy is important to consider. Figure 3-7 shows that 15 miles after starting a trip the fuel economy at 10°F ambient temperature is still only 80% that reached at a fully warmed up 100°F ambient temperature.



Source: SAE 650861, 1965

FIGURE 3–7 FULLY WARMED-UP ECONOMY VERSUS TRIP LENGTH

We attempted to determine what benefits could be derived from devices which controlled engine compartment temperatures as well as radiator and cooling water temperatures. However, we were unable to obtain sound experimental data indicating what fuel economy improvements were possible using these devices. However, devices of this type are available for trucks, buses, and passenger cars and it would appear further work on this subject is in order.

3.3.4.2. Barometric Pressure

Carburetors will be altitude-compensated in the near future, since a decrease of 1-1/4% in the air/fuel ratio occurs for every 1000-foot increase in elevation. We did not consider it necessary to correct for this anomaly in evaluating fuel systems.

Changes in barometric pressures also affect aerodynamic drag and rolling resistance. However, we are unable to obtain usable experimental data to adjust the results of the analytical evaluations. Furthermore, the prime consideration in evaluating improvements of synthesized vehicles was to determine relative improvement over reference vehicles, and we felt this to be unnecessary providing both cars were judged on the same basis.

3.3.4.3. Humidity

The engine's air/fuel ratio can also be lowered if the humidity is increased, but the maximum effect is negligible compared to the effects of normal variations of pressure and temperature. The air/fuel ratio decrease which results from increasing the humidity is caused by the water vapor displacing some of the air flowing into the engine. Humidity plays an important role in carburetor icing.

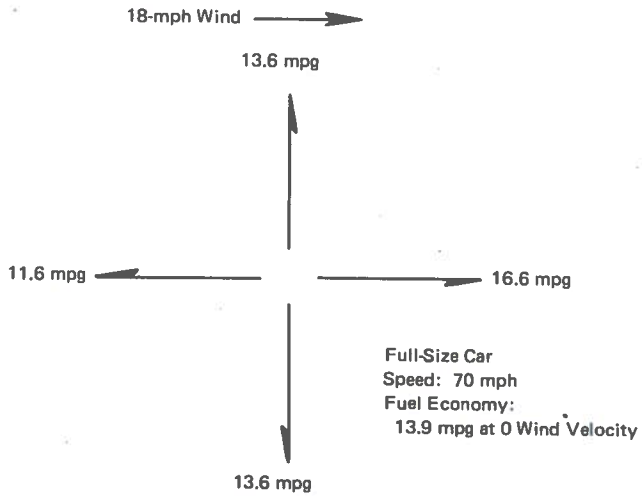
3.3.4.4. Sun Load

Hot fuel handling performance can be severely affected by the amount of exposure to solar radiation during a hot soak. However, no adjustments were made for this factor in our analysis.

3.3.4.5. Wind

Temperatures underhood tend to be lower on windy days as compared to calm days. In addition, carburetor fuel bowls which have external vents tend to dry out more rapidly on windy days, because gas vapors are blown away. With the elimination of external bowl vents on most late model cars, the effect of wind on carburetor dryout has been considerably minimized.

A further consideration is the effect of wind on aerodynamic drag losses. J.J. Cornell[10] presents a specific example (Figure 3-8) for a vehicle traveling at 70 mph. The fuel economy with zero wind is 13.9 mpg; with an 18 mph wind the variation is from 11.6 mpg to 16.6 mpg.



Full-Size Car
Speed: 70 mph
Fuel Economy:
13.9 mpg at 0 Wind Velocity

Source: SAE 65082, 1965

FIGURE 3–8 EFFECT OF WIND ON HIGH-SPEED FUEL ECONOMY

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[10] Cornell, J.J., Passenger Car Fuel Economy Characteristics on Modern Superhighways, SAE 65082, Nov. 1965.

We found in some cases that the experimental data collected for the study had been adjusted to standard ambient conditions for pressure, temperature, humidity, and wind, but in other cases it had not. However, in most cases the data were at least temperature-corrected.

In the analytical portion of our work we made no attempt to vary from standard ambient conditions to keep data to the same reference baseline. However, the reader may wish to refine further the tank mileage results reported when applying the data to selected cases.

3.4. USER/MARKET CONSIDERATIONS

User/market aspects are more qualitative in nature than the technical aspects previously discussed. However, they are still of major importance and must be used in conjunction with the technical aspects to provide a complete evaluation of the individual improvements and synthesized vehicles. Each of these considerations is described below, along with explanations of how they were considered in the evaluation process.

3.4.1. Comfort

The qualitative factors considered relative to comfort include noise level from both the road and the vehicle, ride quality, seating comfort, passenger compartment temperature, control visibility, ease of ingress/egress, and convenience of controls and manipulation. All of these factors were required to be equal to or better than the selected reference vehicle.

3.4.2. Vehicle Size

Vehicle size refers to the passenger compartment and luggage storage space which has to be equal to or larger than that of the selected reference vehicles. Because of the energy crisis there has been an increasing trend by the consumer to purchase smaller vehicles.

3.4.3. Appearance

Appearance refers to the internal and external style and finish. Aesthetically, the improvement should be appealing to the consumer and not represent a dramatic departure from the reference vechicles in style or materials, unless they have been effectively traded off for an equally acceptable benefit; for example, changing the appearance to effect a fuel saving through reduction in aerodynamic drag would be acceptable, if visibility remained the same without degrading vehicle size and passenger comfort.

3.4.4. Cost

Cost considerations were subdivided into three categories as follows: initial cost, operating costs, and life-cycle costs. Additional costs have been – and will continue to be – added to vehicles because of new equipment which has had to be incorporated in the vehicles to meet safety and emission control standards imposed by regulatory control agencies. However, the costs associated with fuel economy are those representing the addition of innovative improvements to the vehicle. These costs have been considered on a life-cycle basis and data are included which show estimates for initial and operating costs. In our opinion, the user should not have to pay life-cycle costs in excess of that needed to gain fuel economy.

The following characteristics are interrelated; however, a relative importance is associated with each and we have listed them in descending order of our selection of their importance.

3.4.5. Reliability

Reliability refers to consistent usage without failure. Major improvement ideas should be equally as reliable as the selected reference vehicles and should be predicated on a goal of no major failures for 100,000 miles of vehicle operation.

3.4.6. Durability

A component can be reliable but not durable. The durability factor should be such that the component or system should be equal in life to a comparable component of the reference vehicle, require no more than routine maintenance for 100,000 miles of operation, and predictable degradation of the component should be recognizable by the user before it affects the vehicle safety and reliability, e.g., the power plant should operate efficiently for 100,000 miles without major overhaul.

3.4.7. Repairability

For purposes of this study the improvement idea or system must utilize the existing skill levels, equipment, and resources presently available and in use by the industry, and repair techniques should have little or no adverse effect on the labor force. We noted whether these criteria were met.

3.4.8. Frequency and Ease of Maintenance

The improvements considered should not require more maintenance than the existing component it replaces. It should not be more difficult to maintain, nor should it be a safety hazard if not maintained by the user. Furthermore, we noted there was a possibility of fuel economy degradation if the component were not maintained properly.

3.5. SPECIAL CONSIDERATIONS – IMPACT ON FUEL SUPPLIES AND THE AUTOMOTIVE INDUSTRY

It has become abundantly clear that a barrel of crude oil saved is better than a barrel of oil imported, and as good as a barrel produced. This is particularly true from the standpoint of the country's economic well-being, national security, and balance of payments. The barrel saved will result from vehicles operating more efficiently using fuels which cost less to refine. We have attempted to indicate where a fuel can be used which costs less to refine in addition to savings actually being made by the vehicle itself. For example, the diesel represents a cost saving both because it is a more efficient engine and because it uses fuel which costs less to refine. However, in producing diesel fuel, certain side effects, such as the overproduction of naphthol, have to be considered.

All aspects of the automobile industry – for example, raw materials, labor, skills, plant and equipment, and suppliers – could be affected by the introduction of certain innovative improvements. For example, one innovation – the introduction of the diesel engine in automobiles – could have wide-ranging effects on the petroleum industry.

Let us suppose that in 1979 we have an automobile force of some 100 million cars with new car production annually reaching 10 million. Let us further suppose that the number of new automobiles sold with diesel engines beginning in 1980, increased as follows:

Year	**Number of New Automobiles Sold with Diesel Engines**
1980	1 million
1981	2 million
1982	4 million
1983	8 million
1984	10 million

In 1972 U.S. petroleum refineries produced about 50% of total product outturn as motor gasoline and 21% of the general category called distillate fuel oil. Within the distillate fuel oil category the following division can be assumed: 60% home heating oil (furnace oil); 20% of diesel fuel sales for trucks, buses, and tractors; and 20% miscellaneous for such categories as railroads, ships, industrial use, etc. These percentages have remained approximately the same for the past 20 years.

Recent fuel shortages have accelerated the introduction of energy conservation by such means as lower thermostat settings in homes and offices, increased installation of insulation and storm windows, switch in full-size car sales to compacts, elimination of gasoline sales on Sunday, and a maximum speed limit of 55 MPH, which will curb respective demands of distillate fuels and motor gasoline. It is premature at this time to estimate the relative percent reductions for each category or the length of time that these conservation measures will remain in effect. Undoubtedly some will have only a temporary effect on demand, while others will be more permanent. We see no reason to predict a major change in the historical ratio that has existed between motor gasoline and distillate fuel sales without a much more detailed analysis. However, there have been recent indications that a logical petroleum allocation system should reserve oil for premium uses such as transportation, petrochemical feedstocks, etc., and reduce consumption via direct combustion for heat generation. Another long-term trend which could expedite this transition might be the introduction of solar energy for home heating purposes which would effect a dramatic reduction in the demand for distillate fuel oil.

Of course, such a scenario would be compatible with the introduction of a diesel engine by the automotive industry.

Since the U.S. refining industry would have significant lead time to plan for the introduction of diesel engines in automobiles, we can see no major supply difficulties in the transition period. If the promised schedule is maintained, by the end of 1984 there would be approximately 25 million cars on the road with diesel engines (or 25% of the total automotive population). If we assume equal fuel mileage for the two engines, the diesel engine for comparable requirements should require less fuel. However, for this hypothetical discussion, the degree of improvement has not been considered. Then this would mean a reduction in U.S. refinery gasoline yield from about 50% to 37.5% with a corresponding increase in the total distillate pool from 21% to 33.5%. One might expect slightly better mileage on a volume basis for diesel fuel since it is a heavier product (greater specific gravity) than gasoline and thus contains more Btu's per gallon.

The natural distillation yields of a typical crude oil processed in the United States can be considered to contain 25% naphtha (gasoline boiling range material), 35% middle distillates (including kerosene), and 40% residual. There should be no problem in reducing gasoline demand consistent with straight-run naphtha availability with a corresponding increase in diesel fuel requirements. Refiners would reduce the conversions of residual and distillate fractions to gasoline. This would mean a savings in refining capital and operating expenses and a reduction of energy consumption within the plant itself which should translate into lower product prices.

It should be noted that expensive quality improvement processes, such as catalytic reforming and C_5/C_6 isomerization, are required to increase the octane number of straight-run naphtha to manufacture today's motor gasolines. The straight-run distillate fractions are generally suitable for diesel fuel blending, but desulfurization is required if the crude oil processed is sour. If residual conversion to distillates is widely practiced in the 1980's, then the cetane number could be a problem for catalytic cracked or visbreaker stocks. However, even this problem could be solved via hydrogenation of the poor quality blend stocks or by purchasing additives (hexyl nitrate and previously amyl nitrate) to increase the cetane number. Thus it would be cheaper to manufacture diesel fuel than motor gasoline.

It would be possible to allow gasoline demands less than the basic 25% straight-run naphtha production for the following reasons: (1) to increase the octane number of straight-run naphtha via catalytic reforming or isomerization, there is a volumetric yield loss of motor gasoline of about 10%; (2) there are speciality product demands from the naphtha pool for such uses as dry cleaning solvents, paint thinners, lighter fluids, etc.; (3) we can expect a major surge in petrochemical feedstock demand from the naphtha fraction. Historically, the U.S. petrochemical industry used natural gas liquid feedstocks as its main supply, but these sources are drying up due to the reduction in natural gas availability. Thus this industry will logically turn to naphtha as a supplemental feedstock that could grow to as much as 10% of product outturn by the mid 1980's; (4) U.S. commercial airlines (which are expected to consume up to 10% of total product demands by the mid 1980's) currently use a kerosene-range jet turbine fuel. It is possible, with minor engine modifications, to switch to a naphtha-based jet fuel (such as is now used by the U.S. Air Force). This would transfer a significant product demand from the distillate to the naphtha pool; however, the relative safety of JP-4 fuel vs. kerosene in airline service is a subject of much controversy, particularly with respect to ground handling and post-crash fires. It may be much better to keep the kerosene fuel in the airliners and the gasoline in automobiles; (5) there have recently been plants built to manufacture synthetic natural gas from naphtha feedstocks to supplement natural gas supplies. Although this process of converting one clean energy form to another is basically an inefficient use of our nation's resources, it is possible that a small naphtha demand for this service will still be required in the late 1980's; (6) naphtha can also be used in the refinery internal fuel system and also as a feed to hydrogen plants to supply hydrogen for desulfurization or hydrocracking of residual stocks to distillate; and (7) the greater usage of distillates, the higher the octane number of the remaining clear stocks for gasoline, thus reducing investments needed for the removal of lead from gasoline motor fuels.

We do not see any problems with petroleum distribution and transportation systems as they already handle distillate fuel oil and diesel stocks. Most gasoline service stations would require the addition of another storage tank and pump if they plan to maintain the present grade structure of motor gasolines during the transition period.

This is just typical of the effects one fuel economy innovation could have on an industry. Similar effects could be ascribed to the other innovations proposed.

4. FUEL ECONOMY TECHNOLOGY

4.1 MEASUREMENT TECHNIQUES

4.1.1. Background and Purpose of Tank Mileage Measurement

The purpose of the work described in this chapter was to develop a practical method for determining the consumption of gasoline by the reference vehicles, or improved vehicles, on the basis of average driving conditions. Our rationale was based primarily on determining the fuel economy or fuel usage of the vehicle being tested over a year's time. Thus our test concept was fundamentally different from the driving cycle technique generally used to test a vehicle over a relatively short period of time or distance.

The term we used to describe the output of this rationale was "tank mileage," a value equated to the total miles driven per year divided by the total gallons of fuel used per year. Having calculated the total gallons that could be saved annually by any one improvement, we were then able to compare that savings against the cost of the improvement to assess whether the improvement was worth examining further.

The approach we took to develop this rationale was predicated on the following:

1. The collection and review of the various economy test procedures presently being utilized by government and industry;

2. Identification of the influencing factors which affect total automobile fuel consumption. (Table 4-1 presents a partial list of influencing factors that were considered in developing the rationale);

3. Performance of a simple statistical evaluation of published reports relating to driving modes and driving cycles from such sources as the Bureau of Public Roads, the American Petroleum Institute, the U. S. Department of Transportation, and the Environmental Protection Agency;

4. Development of a formula – based on the summation of these factors – for determining tank mileage.

We would like to point out that segregating the influencing factors, such as urban driving and steady-state road speeds, greatly simplified the problem of collecting data and analyzing it. In addition, we were also able to combine individual factors in different ways, which allowed us to produce different total miles per year based on the different driving modes reported.

TABLE 4-1

PARTIAL LISTING OF INFLUENCING FACTORS

Physical Conditions	Driving Modes	Driving Habits and Conditions
● Road Surface Condition	● Urban	● Cold Start Versus Hot Start
● % Grade	● Suburban	● Coasting Versus Panic Stop
● Terrain	● Highway	● Normal Acceleration Versus W.O.T.
● Ambient Conditions	● Interstate Thruway	● Passing Maneuver
● Condition of Automobile	● Idling in Congestion	● Overloading

While we feel that our rationale is realistic for determining the fuel consumption of the average car as now driven in the United States, it is possible to modify the influence of say urban driving by increasing the amount of miles accumulated under that condition and reduce the amount of steady-state driving, thus providing the capability of evaluating a concept solely for the city condition or conversely solely for interstate highway usage. Again, it must be pointed out that the rationale developed for this study in our opinion represents the average usage in the course of the year.

In undertaking this study we first emphasized the evaluation of improvements in fuel mileage resulting from a wide variety of changes in the vehicle and power train design parameters. It was a relatively easy matter to calculate the fuel mileage (miles per gallon of fuel – mpg) obtained under steady-speed, level-road driving conditions. However, steady-state speeds alone are not representative of most people's driving habits. The average driver spends a great deal of time under transient conditions: accelerating, decelerating, braking and idling, as well as steady-speed cruising. In an attempt to simulate average customer driving conditions, each of the major automobile manufacturers has established its own driving cycles to simulate city, suburban, country, and interstate highway-type driving. All manufacturers' test cycles are a little different from one another, although they have certain features in common. At the present time there is no universal agreement on a driving cycle (or set of driving cycles) that represents a customer's average driving pattern. However, a committee was recently formed by the Society of Automotive Engineers to consider the establishment of such a universally approved "fuel economy driving cycle."

Up until quite recently, no data existed that would show how vehicles are actually operated on non-metropolitan roads, so the generation of a truly representative driving cycle was precluded. The work done by the Bureau of Public Roads was too general and did not give specific enough information to actually see how the vehicles were driven. To eliminate this deficiency, EPA has recently conducted a test program to develop a non-metropolitan driving cycle. Over 1000 miles were driven on non-metropolitan roads to find out how vehicles are driven. A composite driving cycle has been generated. Unfortunately, this new cycle was not fully developed at the time ADL was performing this study.

In the absence of an approved driving cycle, we decided to use the Federal Driving Cycle (FDC), plus a mix of steady speeds. We felt the FDC would represent the urban driving situation suitably. We selected the fuel mileage over the FDC and the calculations of miles per gallon at steady speeds of 30, 40, 50, 60, and 70 mph on level roads as the operating conditions for evaluating the overall average customer fuel usage. Fuel consumption during idling conditions was counted as part of the FDC mode.

We soon determined that reported fuel usage or fuel economies were dependent on the test procedure to which the vehicle was subjected. The automobile industry and the Government have been using several test procedures for reporting results. This practice, of course, would tend to create anomalies in the reported results and would also raise the question of which test procedure was most representative for all areas of U.S. because of the many influencing factors.

We also recognize that possibly in the near future the results of the S.A.E. study will provide a mix of driving modes which will serve the objective of industry, government, and the general public more realistically.

The fuel economy data for all improvement combinations found in Tables 4-33 through 4-35 can be applied to any new driving cycle conditions that may suit the results of the S.A.E. Committee study.

With this possibility in mind, we investigated the testing procedures in more detail by collecting data on each of the various test specifications being utilized by industry and government.* We performed a review of each test procedure which confirmed our initial contention that although each procedure was valid for the purpose intended, the types of test (i.e., dynamometer, road test or test track, correction factors, warm-up procedure, etc.) were different enough to create variability in the results. Table 4-2 illustrates the variability between the various test procedures. Tables 4-32 through 4-35 (pages 174-177) provide the reader with the necessary data on fuel economy improvement for individual innovations and various combinations of these innovations. On page 168 there is a sample calculation, and Appendix VII includes a display of driving mode and cost for improvement sensitivity calculation.

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*Complete test specifications for various companies are included in the Appendix.

4.1.2. Statistical Evaluation of Published Driving Mode and Rationale Used for Determining Tank Mileage

After careful review of the published information developed by the Environmental Protection Agency and the automotive industry, we judged that the paper generated by Mr. J.D. Murrell,* Assistant to the Director of the EPA's Advanced Automotive Power Systems Development Division, most nearly satisfied the requirement for determining tank mileage for this study.

To arrive at a total annual driving cycle profile Murrell utilized two Federal driving cycles which were developed for exhaust emissions and equipment durability tests: (1) the DHEW Urban Dynamometer Driving Schedule (Appendix A of the November 10, 1970 Federal Register, Vol. 36, No. 55 3/20/71) referred to herein as the FDC-CVS-72; and (2) the EPA "Durability Driving Schedule" (Appendix D of the November 10, 1970 Federal Register) referred to herein as the 11-LAP cycle. He compared these driving cycles with the results of an earlier report[12] and also used other data obtained from the Bureau of Public Roads, American Petroleum Institute. The driving profile he synthesized included a combination of roughly equal proportions of urban driving and rural driving characteristics. The urban portion was a combination of approximately equal proportions of the FDC-CVS-72 and 11-LAP cycles. The rural portion was obtained from 1967 data (Bureau of Public Roads, API) on the distribution of vehicle travel by type of road, where cruise speeds are assigned to each type of rural road to arrive at miles per year at each cruise speed. Murrell's driving profile is presented in Table 4-3. This basic approach is a sound one and it utilizes the available data. The data base described above appears to be adequate to synthesize a driving profile. In fact, it is the only data available which have been collected on a systematic basis by industry and government and have been published.

However, the assignment of single cruise speeds to each type of highway, as shown in Table 4-3, appears somewhat unrealistic, and in Table 4-4 this has been modified by spreading out the mileage on each type of road to cover a speed range. This results in the rural cruise mile profile for all roads shown in Table 4-5.

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*J.D. Murrell, Internal Memo to John Brogan, AAPS/EPA, Jan. 29, 1971.

[12] A Survey of Average Driving Patterns in Six Urban Areas of the United States, System Development Corporation, TM-(L)-4119/007/00, January 29, 1971.

TABLE 4-2

SUMMARY COMPARISON OF FUEL ECONOMY TESTING PROCEDURES

User	Test Load Added to Curb Weight	Vehicle Preparation and Operating Conditions	Type of Cycle	Type of Test	Data Adjustment	Description of Cycle: Length (miles)	Description of Cycle: Time (minutes)	Description of Cycle: Average Speed (mph)
FDC	≈300 lb	12-hr. soak @ 70°F one test w/70°F start 10-min. stop, another test w/hot start Test run at zero and at each 4,000 miles until 50,000 miles accumulated	EPA – C.V.S.	Dynamometer	Reported fuel economy calculated rather than measured.	7.5	22	19.4
FDC	≈300 lb	Used to accumulate mileage between each 4,000-mile emissions test	11-lap durability	Test track	No fuel mileage taken	40.7	81.5	30
A	Driver and Observer	Check and tune-up vehicle not run in rain. 60-mph for 20 miles, preliminary warmup	City route	Road test	Not specified	4.63		
B	No "Ballast" ≃ 175-lb Driver	500-mile break-in	Fuel economy, constant speed, road load	Test track		35		
		700-mile, high-speed break-in	Fuel economy, constant speed, part throttle or grade simulation.	Test track	Not specified	30		
		Cars have min. 500 mile. 10 miles @ 60 mph 5 miles @ 20 mph Tuned up	Fuel economy simulated, interstate operation	Test track		25		
C	600 lb	2,000-mile min. break-in. Tune-up and adjustment 10-mile warm-up at 60-80 mph A.C. off, windows closed.	1) Business district fuel economy driving schedule.	Test track	Temperature corrected to 60°F.	2	7.6	16
			2) Suburban fuel economy driving schedule	Test track	barometric & humidity corrected, based on engineering judgment	3.7	9.3	24
			3) Highway fuel economy driving schedule	Test track		11.3	18.9	47
			4) Interstate fuel economy driving schedule	Test track		14.9	12.8	70
D	+300 lb	Tune-up and adjustment, A/C off, lights on low beam	City	Test track	Corrected to base of 60°F – 28.7 in. Hg	7 46		16
			Suburban	Test track		10 4		42.5
			City Suburban	Computed average		17 86		

TABLE 4-3

DRIVING PROFILE*

Miles Per Year	Reference Driving Cycle
2,730	(FDC CVS-72)
2,700	11-Lap
1,000	40 mph State rural highways (Bur. Pub. Roads)
840	50 mph Interstate urban highways (Bur. Pub. Roads)
1,840	60 mph U.S. rural highways (Bur. Pub. Roads)
890	70 mph Interstate rural highways (Bur. Pub. Roads)
10,000 Total Mileage	

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*J. D. Murrell, Internal Memo to John Brogan, AAPS/EPA, Jan. 29, 1971.

TABLE 4-4

ASSIGNMENT OF CRUISE SPEED MILEAGE TO "RURAL" DRIVING

Type of Road	Miles Per Year	Cruise Speed (mph)	Mileage
State Rural	1,000	40	550
		50	450
Interstate Urban	840	40	90
		50	450
		60	300
U.S. Rural	1,840	50	770
		60	1,030
Interstate Rural	890	60	250
		70	540
		80	140
Total	4,570		4,570

TABLE 4-5

"RURAL" CRUISE SPEED PROFILE – ALL ROADS

Cruise Speed (mph)	Miles Per Year
40	640
50	1,670
60	1,580
70	540
80	140
Total	4,570

The driving profile shown in Table 4-3 is a useful split of driving conditions for the analysis of a 10.000-mile-per-year usage of an automobile. However, computer simulation of both the FDC-CVS-72 driving cycle and the 11-lap driving cycle was felt to be an unnecessary complication and an effort was made to accommodate the 11-lap driving cycle without extensive computer programing. Some 74.3% of the 11-lap driving cycle was run at a steady speed and the entire driving cycle was run at an average speed of 30 mph. We decided to divide the 11-lap driving cycle into a steady-speed component of 30 mph and a start-and-stop mode which is simulated by the FDC-CVS-72 driving cycle so that extensive computer modelling to include the 11-lap driving cycle would be alleviated.

The resulting driving profile then looks like the first row of Table 4-6. However, the federal law limiting the automotive speed limit to 55 mph will undoubtedly reduce the annual mileage of the higher speeds, and we estimate that this will result in the driving profile shown in the second row of Table 4-6.

TABLE 4-6

TOTAL DRIVING PROFILE – MILES PER YEAR

		Miles Per Hour					
	(FDC-CVS-72)	30	40	50	60	70-80	MPH
Before 55-mph Limit	3330	2100	640	1670	1580	680	
After 55-mph Limit	3300	2100	1000	1900	1300	400	
% of Total Miles per Year	33	21	10	19	13	4	

The process carried out above in arriving at a driving profile may be summarized as shown in Figure 4-1. It should be noted that in this approach we did not include factors such as cold starts or the effects of wind, weather, road conditions, grade, and the like. Therefore, in evaluating the relative improvement of individual devices and synthesized vehicles, we will use the mix of FDC-CVS-72 miles and steady-state cruise from 30 through 70/80 mph as shown in line 2 of Table 4-6. The evaluation of the FDC fuel consumption was made by the use of the computer simulation, a description of which follows. Although alternative methods of evaluating the FDC fuel consumption are mentioned, e.g., Section 4.1.4., the computer program was the only tool used. The reader may wish to make his own evaluations by varying the mix of FDC-CVS-72 and steady-state to suit certain specific conditions, such as 100% urban driving to 100% interstate driving at 70 mph. (See pages 177-181 and Appendix VII for sample calculations and data.)

4.1.3. Computer Simulation of Fuel Economy and Performance

4.1.3.1. Background Description

Computer simulation provides a useful tool for determining vehicle fuel use over a wide variety of different operating conditions. The simulation we used was originally created specifically to perform fuel economy and emission calculations* for vehicles operating over the FDC, but it will accept any chosen driving cycle as input if expressed in the required format.

The objective of the computer program used for vehicle simulation in this study was to predict the fuel consumption characteristics of any synthesized vehicle design over various specified

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*The program was operated by Scientific Energy Systems Corp.,while the program was designed to include calculations of emissions for an automotive steam engine, it was beyond the scope of this study to construct good transient emissions models for the spark ignition gasoline engine because of the variety of approaches taken by the automobile manufacturers. Therefore, no attempt was made to simulate exhaust emissions for this study.

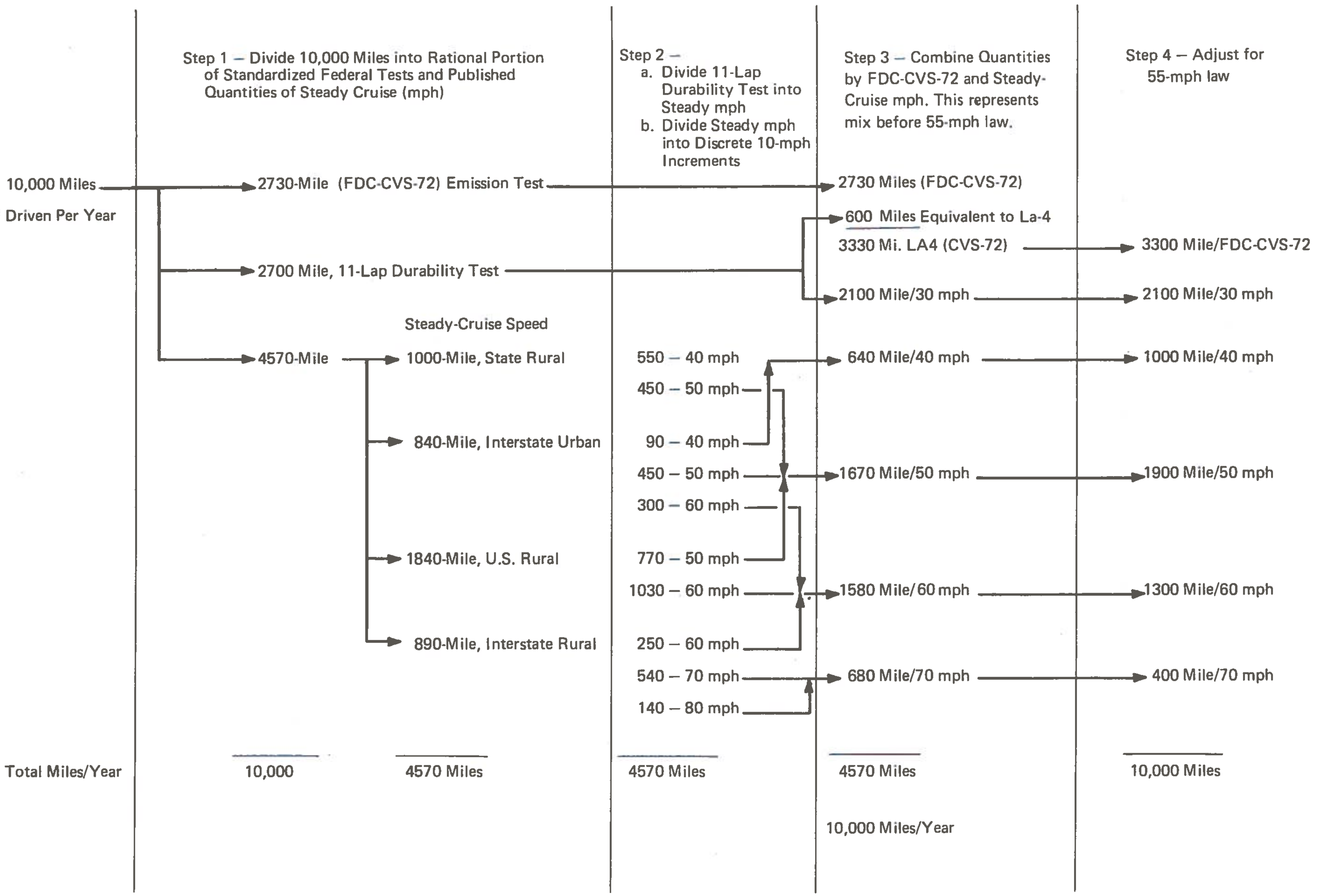

FIGURE 4–1 SCHEMATIC OF DEVELOPMENT FOR MIX OF MILES DRIVEN PER YEAR

transient operating conditions and during steady-speed, level-road driving. The steady-state driving is, of course, a special case of transient operation (acceleration = 0). Thus, the following discussion has been directed toward a description of the transient case. It is desired to simulate vehicle operation over a specified driving pattern (driving cycle) which may consist of a combination of transient and steady-state operating conditions, as required. Since it was desired to run the simulation program over the Federal Driving Cycle (FDC) employed by the EPA for exhaust emissions certification, the computer program was written to conveniently accommodate the FDC. The FDC data have been tabulated in a table of values for vehicle velocity versus time consisting of 1371 points (one for each second of the driving cycle). Salient characteristics of this cycle are:

7-1/2 miles long
22.8 minutes
Average Speed = 19.7 mph

Maximum speed = 56.7 mph
No. times at idle = 18
No. minutes at idle = 4.33

To simulate operation of an automobile over a specified driving cycle to determine fuel consumption, we had to –

1. Determine the sequence of engine operating conditions necessary to make the vehicle follow the specified driving cycle,

2. Determine from a steady-state engine map the instantaneous rate of fuel flow for each instant of time over the driving cycle,

3. Integrate the instantaneous fuel flow versus time and vehicle velocity vs. time to obtain the total fuel consumed and total distance traveled, and

4. Obtain fuel economy by dividing the total miles traveled by the total number of gallons of fuel consumed.

To carry out step 1, we had to utilize reliable input data to describe the following vehicle, drive train, and powerplant characteristics:

Input Data Required

1. Vehicle road load power requirements
    a. aerodynamic drag characteristics,
    b. rolling resistance characteristics.
2. Drive Train Component Efficiencies –
    a. Tire Efficiency (if road load characteristics determined by towing test).
    b. Rear axle efficiency,
    c. Transmission efficiency,
        i. gear box bearing and gear losses for automatic transmissions,
        ii. torque converter characteristics and losses,
        iii. gear box spin losses,
        iv. front pump losses.
    d. Transmission shift logic,

- e. Accessory power requirements,
  - i. radiator fan,
  - ii. alternator,
  - iii. power steering pump,
  - iv. air conditioner,
  - v. other.
- f. Engine operating map,
  - i. Torque vs. speed and manifold vacuum,
  - ii. Fuel flow vs. torque and speed.

The computational sequence utilized in the simulation program is illustrated in the flow diagram of Figure 4-2. The various computational steps are illustrated by the blocks in the left hand column of the diagram whereas the input data utilized for each computational step are listed in the right hand column. The federal driving cycle is broken down into 1371 separate time increments, one for each second of the cycle. During each of these time intervals the engine power and speed necessary to allow the vehicle to travel at the defined average velocity and acceleration were determined. From this information the fuel consumed during each time interval was calculated and summed up to obtain fuel economy over the entire cycle.

Figure 4-2 illustrates the solution steps for a typical time interval during the cycle as follows:

1. First the average vehicle velocity and acceleration were computed from the initial and final velocities specified by the input drive cycle definition;

2. Wheel torque and RPM were determined from (a) empirical equations expressing the steady-state aerodynamic drag and rolling resistance characteristics of the vehicle and from (b) vehicle inertia characteristics using selected numerical values for vehicle test weight, drag coefficient, and frontal area. Vehicle inertia consists of both vehicle weight and polar moment of inertia of all rotating parts of the drive train;

3. Torque and RPM at the transmission output shaft were then determined by applying axle ratio and axle efficiency parameters;

4. By consideration of transmission gear ratios, shifting logic, gear and spin losses, the speed and torque at gear box input shaft were then determined. If the transmission included a torque converter, its characteristics, such as torque ratio, and speed ratio vs. K factor, were used to obtain engine output shaft torque, and speed required. The transmission front pump loss was also included when appropriate.

5. Next the engine accessory power consumption was determined for the required engine RPM. Accessory component torque loads were typically input as being solely a function of engine RPM. Adding this load to the engine output shaft power gave the gross engine output;

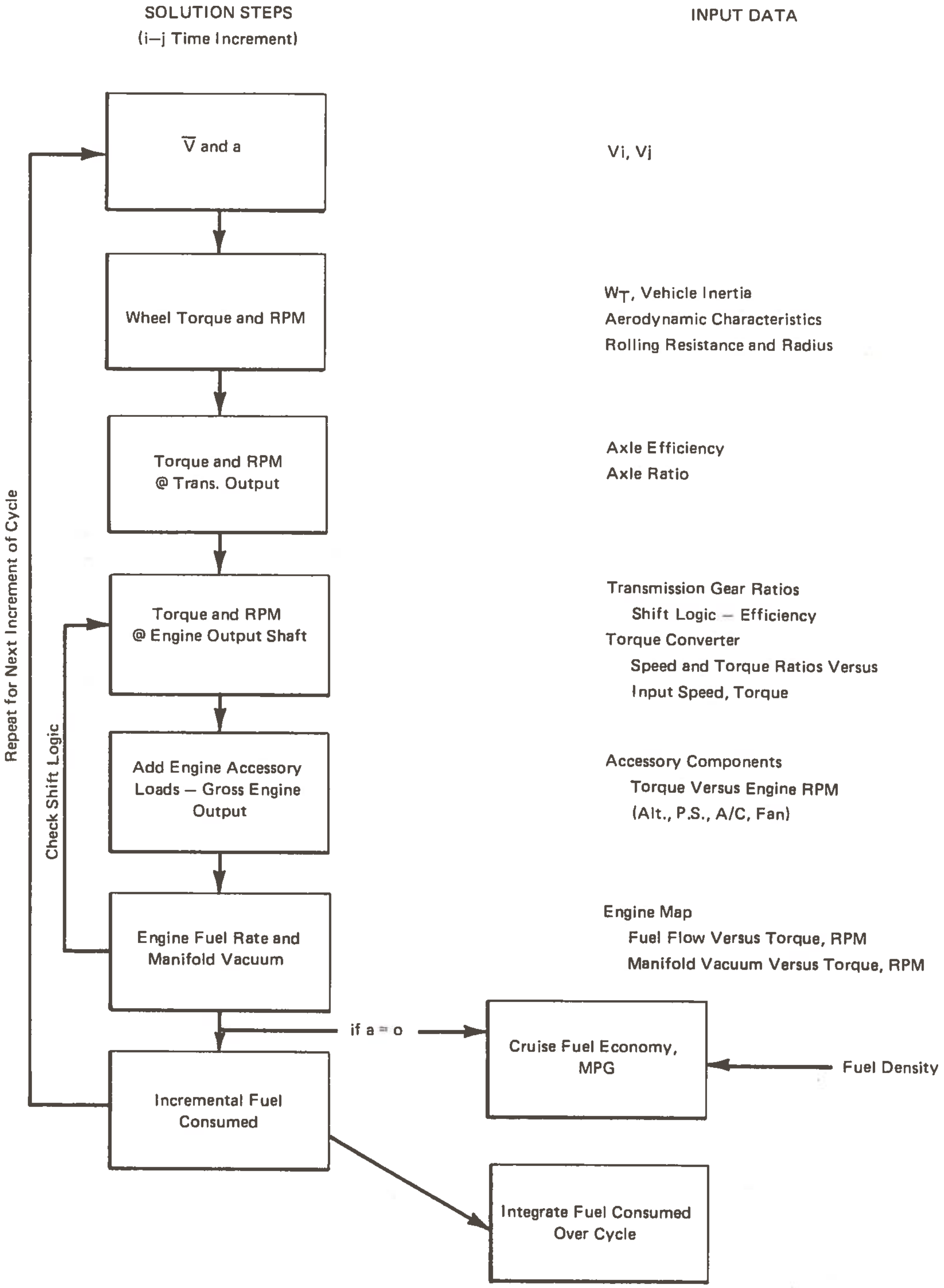

FIGURE 4–2 FLOW DIAGRAM OF COMPUTER SIMULATION

6. The instantaneous engine fuel rate was then determined from an engine map expressing fuel flow as a function of gross output torque and RPM;

7. If steady-speed fuel economy was being calculated for zero acceleration, then the miles per gallon of fuel were calculated from the vehicle speed, fuel flow rate, and the appropriate fuel density;

8. If a driving cycle calculation was being performed, the fuel consumed during the 1-sec. interval was computed and added to the previously accumulated fuel consumed, whereupon the program indexes to the next 1-sec. interval of the driving cycle and repeats the above eight calculation steps.

At certain points in the driving cycle, the vehicle was brought to a stop and the engine idled for a finite period of time before accelerating again. During this period the above calculation procedure was by-passed and an idle fuel flow value was used. Also during rapid decelerations where engine braking (which is incorporated in the engine map treatment) was insufficient, and the brakes must be applied, the idle fuel flow is assumed.

After indexing through the entire driving cycle and making the above calculation for each time increment, the total distance traveled was divided by the total fuel consumed to obtain the miles per gallon fuel economy over the driving cycle.

A typical computer output summary sheet is shown in Figure 4-3. Each separate computer run is identified by a "calculation number" hereinafter referred to as "run no.," followed by the vehicle identification, engine identification, accessory loads, torque converter identification, transmission identification, tire identification, axle ratio, road (curb) weight, test weight, and transmission gear ratios. Three items of interest in the upper right corner are the vehicle frontal area (area-ft^2), the drag coefficient (CD), and the engine displacement (DISP).

The output results for steady-speed level "road load performance" are given in a table listing the following parameters as a function of vehicle speed from 20 to 90 mph in increments of 5 mph.

Engine RPM, torque converter speed ratio,
Engine HP, BSFC, fuel flow, and
Tractive force at wheels, fuel economy-MPG.

Finally, the fuel economy over the federal driving cycle is printed at the bottom of the page and is labeled "EPA Cycle."

4.1.3.2. Capability of Simulation Program and Limitations

The computer simulation system described above is basically capable of estimating the overall vehicle fuel economy (miles per gallon of fuel) for operation over any prescribed driving cycle consisting of accelerations, steady-speed cruise, decelerations, and idle conditions interspersed in

```
.F.S. PROGRAM FOR FUEL ECONOMY OVER FEDERAL DRIVING CYCLE                DATE = 11/29/73

CALCULATION NUMBER                  601                              PWR              .4600    CGW
VEHICLE IDENTIFICATION        COMPACT REFERENCE VEH - X CO           GRADE           0.0000    WIND
ENGINE IDENTIFICATION         X COMPANY COMPACT                      AREA           21.4200    CD
ACCESSORY LOADS               X COMP. COMPACT                        ECONID      .00017000
CONVERTER IDENTIFICATION      X COMP. 11.25 IN. TC                                             GNOXI     0
TRANSMISSION IDENTIFICATION   X COMP. - 3 SPEED AUTOM.               GCOI       0.00000000    GHCI      0
TIRE IDENTIFICATION            6.45 X 14 BIAIS PLY                   MU              0.0000    DISP
AXLE RATIO             2.7900                                        START          20.0000    STOP
ROAD WEIGHT =     2851.0000      TEST WEIGHT =    3351.0000          KEYRR                1    EXP      0.
      TRANSMISSION RATIOS                                            KEY                  3    KEY3
          GEAR    GEAR RATIOS                                        WMUPG           0.0000    TGAL3
            1       2.4600                                           WMUPN           0.0000    TNOX3
            2       1.4600                                           WMUPC           0.0000    TCO3
            3       1.0000                                           WMUPH           0.0000    THC3

ROAD LOAD PERFORMANCE

 SPEED    ENGINE    CONVERTER  ENGINE      BSFC      FUEL     FORCE      FUEL       NOX       CO        HC
  MPH      RPM        SPEED      HP        LBS/      FLOW     REQUIRED   ECONOMY
                      RATIO              BHP-HR     LBS/HR    LBS        MPG      GR/MILE   GR/MILE   GP/M
 20.00     949.73     .8437     6.003     .8500     5.1020    63.0467   24.9550
 25.00    1103.18     .9039     7.549     .7654     5.7774    68.7096   27.5468
 30.00    1288.06     .9251     9.539     .7172     6.8409    75.6310   27.9175
 35.00    1474.33     .9394    11.893     .6777     8.0598    83.8107   27.6446
 40.00    1663.17     .9486    14.682     .6411     9.4122    93.2489   27.0543
 45.00    1854.86     .9541    17.970     .6281    11.2877   103.9455   25.3790
 50.00    2046.73     .9584    21.792     .6139    13.3792   115.9006   23.7906
 55.00    2241.14     .9608    26.234     .6007    15.7600   12[illegible].1140   22.2163
 60.00    2437.44     .9620    31.358     .5872    18.4146   143.5859   20.7422
 65.00    2635.10     .9631    37.198     .5808    21.6035   159.3162   19.1538
 70.00    2832.90     .9640    43.817     .5719    25.0596   176.3050   17.7824
 75.00    3031.79     .9648    51.274     .5585    28.6385   194.5521   16.6716
 80.00    3231.92     .9656    59.630     .5665    33.7788   214.0577   15.0769
 85.00    3433.55     .9662    68.947     .6182    42.6202   234.8217   12.6961
 90.00    3636.92     .9669    79.286     .6683    52.9864   256.8442   10.8130

THE SUBURBAN ROUTE (20,30,40 AVERAGE) ECONOMY, 26.6423

THE COUNTRY  ROUTE (50,60,70 AVERAGE) ECONOMY, 20.7717

THE AVERAGE FUEL ECONOMY DURING THE EPA CYCLE = 17.45 MPG
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FIGURE 4–3 TYPICAL COMPUTER OUTPUT SUMMARY SHEET any prescribed manner. While the program is capable of accepting any driving cycle within the performance capability of the input vehicle, the federal driving cycle used by EPA for emissions certification is the only one used to date for calculations. The program also computes level-road, steady-speed fuel economy over a range of vehicle speeds. Since the program developed by S.E.S. was not capable of computing wide-open throttle (WOT) acceleration performance, separate analytical calculations were made to determine if performance criteria were met. These calculations were checked by use of a program made available through the Department of Transportation.

No provisions were made in the simulation to account for excess fuel used during engine warm-up due to choking, higher engine friction, etc., or for excess fuel used by the carburetor accelerator pump which provides richer fuel-air mixtures during rapid acceleration transients. Moreover, the program does not account for extra energy dissipation in the transmission during shifting transients or for clutch slippage, wheel slippage, etc. However, in spite of these limitations, the simulation program was found to provide a reasonably good agreement with manufacturers' test data and proved to be a useful tool for rapid, low-cost examination of the effect of various system changes on vehicle fuel economy.

4.1.3.3 Accuracy Check of Computer Simulation

The accuracy of the simulation program in predicting vehicle fuel use is basically dependent on the quality of the input data used to describe the performance of the various individual components of the vehicle. When accurate input data are employed, good agreement can be obtained between simulation results and test data. Three methods were employed for checking the accuracy of the simulation.

1. Check against manufacturers' test data for steady-speed miles per gallon (mpg) on reference vehicles;

2. Check against EPA certification data for average miles per gallon over the federal driving cycle; and

3. Check of sensitivity coefficients for effect of single parameter changes in vehicle weight, axle ratio, and aerodynamic drag against values reported in the literature by various vehicle manufacturers.

Four reference vehicles were analyzed by computer simulation:*

Company X Compact – run 601
Standard – runs 701 and 702

Company Y Compact – runs 302, 306, and 311
Standard – run 401

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*See Appendix V, Section 2.2.3, Pages 209-211a, for description and verification of computer simulation program.

The results are summarized and compared with manufacturers' test data for steady speed (and, in two cases, a city/suburban test cycle) on the reference vehicle summary sheets (SS-1, -2, -3 and -4 in Appendix V, Section 4.1, and Appendix A). Examination of these sheets will reveal that the simulation and test results always agree within about 10% and, in most cases, within 2-5%. This is considered to be excellent agreement considering the degree of sophistication of the analytical model.

Of even greater interest is to determine whether the simulation can predict the correct relative effect of various vehicle changes on fuel economy. This type of check on simulator accuracy was performed by examining a number of single parameter changes in the reference vehicles (e.g., reduced weight, aerodynamic drag, axle ratio, and rolling resistance) and comparing the results with published results of a similar nature based on work reported by the various automobile manufacturers. The results of this exercise demonstrated that not only do the quantitative effects of single parameter changes in vehicle characteristics agree well from one reference vehicle to another, but also these effects are in good quantitative agreement with results reported by the auto manufacturers. This favorable comparison greatly enhances the value of the computer simulation as a tool for examining the relative effect of system changes on vehicle fuel economy.

4.1.4 Alternate Analytical Method (Algorithm) for Estimating Fuel Consumption

An alternate approach was taken as a means of checking the output of the computer simulation program. This approach was based on a paper delivered by Clayton La Pointe.[13] In his paper, La Pointe developed a statistical analysis of the federal driving cycle exploring four parts: (1) a cruise mode, (2) an acceleration mode, (3) a deceleration mode, and (4) an idle mode. La Pointe determined that approximately 22% of the distance in the federal driving cycle (FDC) is associated with accelerations, 60% with cruise, and 18% with deceleration. The idle mode, added to the acceleration cruise and deceleration modes, comprises approximately 18% of the total 1372 seconds of the FDC.

Further analysis of the FDC shows that the acceleration mode consists of 33 separate accelerations. As La Pointe shows, each acceleration may be viewed as an average 1.46 mph/sec acceleration over 1.67 miles, whereas the actual FDC consists of a wide range of accelerations. These and the statistics on the other three modes are shown in Table 4-7. By using the breakdowns shown in Table 4-7 under the mean conditions of each of the modes, a simple algorithm for approximating federal driving cycle fuel consumption has been developed.

TABLE 4-7

BREAKDOWN OF FEDERAL DRIVING CYCLE BY MODES

	Mode of Operation					
	Accel.	Decel.	Cruise	Idle		Total
% Distance	22	18	60	0	=	100%
By Mode	1.64	1.35	4.47	0	=	7.46 miles
% Time	23	20	39	18	=	100%
By Mode	316	274	535	247	=	1372 sec.

The algorithm for approximating the FDC fuel consumption profile is given in Table 4-8. The acceleration mode consists of 33 accelerations each lasting approximately 16 seconds from 0 to 23 mph at 1.46 mph/sec acceleration. The net number of gallons for this acceleration summed for 33 such accelerations constitutes the total gallons consumed for acceleration. Next the deceleration and idle modes are calculated. Both these modes are based on time rather than distance since the approximation is that during deceleration the car experiences the idle fuel consumption in gallons per hour. We recognize that the assumption regarding fuel usage during deceleration may be more accurately related to manifold vacuum, but we were unable to accommodate this factor. The amount of fuel consumed for the deceleration and idle modes is given by the idle fuel economy for 521 seconds. This is the second of the three major parts of the simple algorithm. The cruise part of the FDC is approximated by 0.148 hour at 30 mph. This is entered as the third and last part of the simple algorithm. The sum of the three modes for the acceleration, deceleration and idle, and cruise modes is added in gallons for the 7.46 total miles traveled, and then the net fuel economy in miles per gallon can be calculated.

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[13] La Pointe, C., Factors Affecting Vehicle Fuel Economy, Automotive Emissions Office, Ford Motor Co., Combined SAE Fuel Lubricating Meeting and Manufacturing Forum, Milwaukee, Wisconsin, September 11, 1973.

TABLE 4-8

TABULATION OF FUEL CONSUMPTION FOR FDC SAMPLE CALCULATION FOR CO. X 400-cid VEHICLE

Acceleration Mode	
Each acceleration requires 7.83×10^{-3} gal. 33 of such acceleration consume	.258 gal.
Deceleration and Idle	
From manufacturers' data the idle fuel consumption is 1.08 gal/hr Sustained for 521 sec. This means	.156 gal.
Cruise	
Fuel consumption for steady 30 mph driving is 1.53 gal/hr, sustained for .148 hrs. This means	.226 gal.
Total Consumption	.640 gal
Total Miles	7.46 miles
Average MPG	11.69 mpg

Sample calculations with four reference vehicles are compared to computer results in the following sections and show about a 10% deviation from the predicted computer results. This correlation demonstrates the feasibility of using a simple algorithm for evaluating automobile fuel economy for the FDC fuel consumption profile, although this was not used for this program.

4.1.5 Sample Calculation for Simple Algorithms for Fuel Consumption Calculation

Table 4-8a presents calculations of the fuel consumed in a single acceleration to 23 mph of the Co. x 400 cid reference vehicle. The vehicle parameters must be calculated at each second during the acceleration. For each of the time increments the transmission and torque converter speeds and rpm's must be calculated in order to determine the engine operating conditions. Once the engine torque and speed have been determined, the fuel map for a particular car provides the fuel flow and thus the fuel consumption during that time period. In the first second the car is stationary; the transmission is stationary; and the engine is providing speed and torque into the torque converter which is shown in the time period zero of Table 4-8a. The torque delivered to the rear wheel then provides a 1.46 mph/sec acceleration at the rear axle which requires a drive shaft of 49 rpm and subsequent torque converter and engine speeds as shown in this table. At each second the combination of engine torque and rpm is used to find the fuel flow in pounds per hour. The total fuel consumption for an acceleration mode is determined graphically as shown in Figure 4-3a. Here the pounds per hour of fuel flow during the acceleration is graphed for the duration of the acceleration. This then is graphically integrated to give the total gallons consumed in a single acceleration to 23 miles per hour at 1.46 miles per hour per second. This then becomes the entry for the acceleration mode. In this particular example, 7.83×10^{-3} gallon was consumed during a single acceleration. Therefore, after 33 such accelerations the vehicle should consume about 0.258 gallon. This quantity is entered into the acceleration mode calculation as shown in the tabulation of fuel consumption for FDC sample calculations (Table 4-8).

TABLE 4-8a

FUEL CONSUMPTION CALCULATION FOR PART THROTTLE ACCELERATION OF Co X 400-cid REFERENCE VEHICLE

			Torque Converter		Engine		
Second	MPH	Drive Shaft RPM	T*	RPM	T*	RPM	Fuel**
0	0	0	68	0	33	600	7.0
1	1.46	49	68	122	36	625	7.0
2	2.96	100	68	247	39	700	7.0
3	4.38	148	68	366	40	760	7.0
4	5.84	197	68	485	47	825	7.03
5	7.30	245	68	580	52	915	7.05
6	8.76	295	68	727	57	1000	9.76
7	10.22	347	115	509	75	1020	10.38
8	11.68	395	115	590	79	1050	11.25
9	13.14	446	115	652	84	1100	11.56
10	14.6	496	168	496	105	1150	13.16
11	16.06	545	168	510	107	1170	14.0
12	17.52	595	168	595	111	1210	14.7
13	18.98	642	168	650	113	1250	15.3
14	20.44	692	168	705	115	1270	15.9
15	21.4	720	168	740	117	1300	16.2
16	23.36	794	168	794	120	1325	16.77

*T is torque in ft-lb.

**Fuel is fuel consumption in lb/hr

The next element of the simulation of the Federal Driving Cycle fuel consumption is the deceleration and idle fuel consumption. From the manufacturer's data the idle fuel consumption is found to be 1.08 gal/hr. From the approximation determined from La Pointe's paper[11] the deceleration consumption and the idle consumption are considered to be the same; their total duration is 521 seconds of the Federal Driving Cycle. Therefore, 0.156 gallon can be assessed to the deceleration and idle mode of the Federal Driving Cycle.

The final entry for the sample calculation is the fuel consumption for a 30 mph steady speed over 4.45 miles. From the manufacturer's data it is found that during a steady speed of 30 mph the company "X" 400-CID vehicle consumes approximately 1.53 gal/hr. This is sustained for 0.148 hour requiring a consumption of 0.226 gallon.

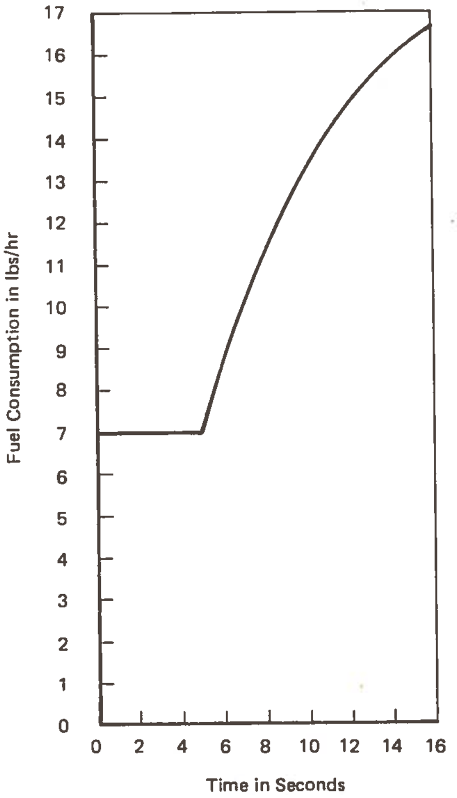


FIGURE 4–3a FUEL CONSUMPTION PROFILE DURING PART THROTTLE ACCELERATION ON Co X, 400 C.I.D. REFERENCE VEHICLE

Adding the three modes of consumption gallons, a total consumption of 0.64 gallon is predicted. This is sustained for 7.46 miles, meaning that the average fuel consumption for this simulation is 11.64 miles per gallon. This compares very favorably with the predicted Federal Driving Cycle fuel consumption for this vehicle of 11.60 miles per gallon. Similar calculations results in Table 4-8b with the other reference vehicles verify that this simple algorithm provides an approximation to the Federal Driving Cycle within about 10% of the predicted computer results.

TABLE 4-8b

COMPARISON OF RESULTS OF HAND CALCULATION OF FDC FUEL CONSUMPTION ALGORITHM WITH COMPUTER SIMULATION

	Fuel Consumed in M.P.G.		
Reference Vehicle	Algorithm	Computer	% Deviation
Co. Y 250	15.1	13.8	9.4
Co. Y 350	11.3	10.4	8.6
Co. X 400	11.6	11.0	5.4
Co. X 250	18.2	17.5	4.0

4.2 FUEL USAGE AND FUEL ECONOMY OF REFERENCE VEHICLES

Over the years a number of papers have been written describing where the power or energy is used in the passenger automobile. The studies have revealed that of the energy released by the burning of the fuel in the form of heat approximately 20% of that heat is used to propel the vehicle when traveling at a steady cruising speed of 50 mph. The other 80% represents heat rejected to the atmosphere and energy consumed by engine friction and the accessories and auxiliaries which are attached to the engine. Figure 4-4 illustrates this heat balance for speeds from 30 to 80 mph. It must be remembered that at a steady speed of 50 mph the throttle is partially open and the engine is only partially loaded. In the case of the conventional spark ignition gasoline engine, this would not represent maximum efficiency.

However, the point that only 20% of the energy is being put to useful work in the conventional passenger car as compared to 40% in the most efficient heat engine application indicates that the greatest opportunity for reducing fuel usage lies in improving the efficiency of the prime mover – the engine – if the vehicle weight is fixed. Of course, while improving aerodynamic drag, rolling resistance, drive train efficiency, and weight reduction are important to consider, the engine remains as the key to a major reduction in fuel consumption.

Before examining in detail how the fuel is used in the reference vehicles it would be well to review the general way in which the energy is partitioned between the engine and the rest of the vehicle.

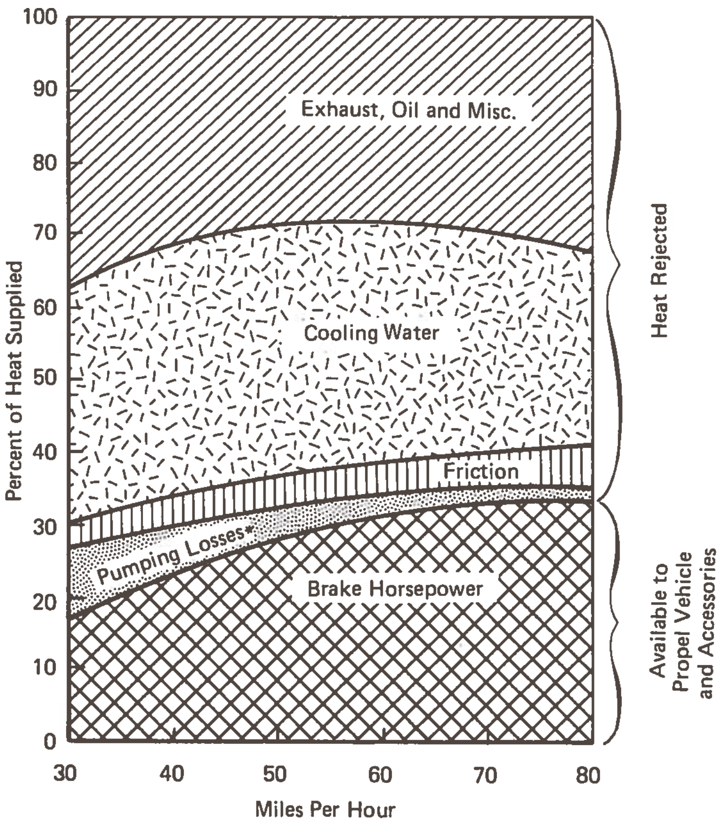
4.2.1 Where the Energy is Used within the Engine

An understanding of the fundamentals of the internal combustion engine is helpful when considering the partitioning of the energy obtained from the fuel. Therefore, what follows is a simplified explanation of the nature of the production of useful power from a spark-ignited internal combustion engine.

The internal combustion engine extracts work from the release of energy effected when the fuel vapors burn in the engine. The resulting expanding gases of combustion drive the pistons of the engine in the cylinders. Thus useful work is extracted from the combustion process through the rotation of the crankshaft which is driven by the piston rods. The gases expand from a compressed volume in the cylinder to the total volume swept out by the movable pistons. The duration and extension of expansion of the gases against the piston determine the amount of work derived from the combustion process. The compression ratio is a measure of the amount of expansion that these gases undergo. Therefore the compression ratio determines the ability of the engine to extract energy from the combustion of fuel.

In a theoretical, ideal engine, about 60% of the thermal energy of the fuel is available as useful work for an engine with a compression ratio of about 10 to 1. Although higher compression ratios will improve this efficiency, in the practical operating engine the compression ratio is limited because of self-ignition or detonation of the fuel.

Therefore, an upper limit of approximately 60% useful work can be ascribed to the theoretical, ideal internal combustion engine. However, this level of efficiency represents an engine operating without heat losses to the lubricating oil, or cooling water, and without energy being consumed by friction or by pumping losses. It also assumes perfect fuel/air mixing, a perfect chemical balance of the fuel/air mixture, and an ideal distribution of the fuel/air mixture to the cylinders.



*Pumping losses occur during the intake stroke and partial throttle settings and result from the piston pushing against the atmospheric pressure in the crankcase offset by partial vacuum in the combustion chamber.

Source: Modified chart from *The Engine – The Power Source,* SAE 779 Part I, Vol. 65, 1957.

FIGURE 4–4 HEAT BALANCE, CRUISING SPEED

While the current spark ignition engine employed in most automobiles is a highly developed machine which delivers good efficiency, we can see that about 35% of the energy is lost to the exhaust system and lubricating oil in the form of heat, about 30% to the cooling water, and about 10 to 12% is lost in pumping and friction. The loss of energy to the cooling system and friction losses which otherwise could have been turned into useful work results from the mechanical design of the engine, particularly the cylinder and piston assembly. Because of the high combustion gas temperatures within the cylinder, a cooling system is provided to remove excess heat to prevent high cylinder wall temperatures and possible hot spots which could result in uncontrolled ignition of the fuel/air mixture as it is injected into the cylinder. The second reason is to assure the longevity of the mechanical components by reducing the corrosive and chemically reactive environment of the cylinder.

The frictional losses in the engine are strongly dependent on the operating conditions of the specific engine. In general, higher engine speeds or higher engine torques at low speed result in higher frictional losses in the power plant.

4.2.2. Breakdown of Fuel Consumption of Reference Vehicles

The previous section was based on summarizing information from a number of sources on how the energy is partitioned between wasted heat and useful work. It showed that about 70% of an engine's available energy is lost in the exhaust gas, cooling water, and friction. Having examined this concept in a general way for a wide range of vehicle sizes, we will now examine and compare the four reference vehicles used on the basis of brake thermal efficiency. Table 4-9 indicates that the development of useful work by the four reference vehicles over the engine operating range based on the heating value of gasoline, and the brake specific fuel consumption. The BSFC is defined as the pounds of fuel consumed per hour per brake horsepower delivered. The heating value of a pound of gasoline is 19,200 Btu as given by Taylor.[14] Therefore since the thermal efficiency is

$$\eta_T = \frac{\text{Brake Energy Delivered}}{\text{Fuel Energy Consumed}}$$

then

$$\eta_T = \frac{1}{\text{BSFC}} \quad \text{X} \quad \frac{2{,}546 \text{ (Horsepower to Btu/hr Delivered)}}{19{,}200 \text{ (Btu/Hr Consumed per lb/hr of fuel)}}$$

$$\therefore$$

$$\eta_T = \frac{1}{\text{BSFC}} \quad . \ 1326$$

A maximum efficiency of 25 to 32% for a open throttled loaded engine is characteristic for the four vehicles and a low end efficiency characterized by a almost closed throttle lightly loaded engine at 800 rpm and 10 hp, ranges from 18 to 22% for the four reference vehicles. The variation between maximum and minimum efficiency is primarily due to the operating conditions of the engine which increase the mechanical friction or increase the engine pumping friction loss, the sum of which reduces the overall efficiency of the system.

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[14] Taylor, C.F., The Internal Combustion Engine in Theory and Practice, 2d Edition, Vol. I, MIT Press, Cambridge, Mass., 1960-1966.

TABLE 4-9

COMPARATIVE MAXIMUM AND MINIMUM BRAKE THERMAL EFFICIENCY OF REFERENCE VEHICLES (WITH ACCESSORIES BUT NO A/C)

	Min BSFC*	BSFC at 800 rpm and 10 hp	Max. Efficiency	Efficiency at 800 rpm and 10 hp
Co x 400 CID	.42	.75	32	18
Co x 250 CID	.43	.60	31	22
Co Y 250 CID	.53	.65	25	20
Co Y 350 CID	.53	.75	25	18

*Brake Specific Fuel Consumption (lb fuel/bhp-hr)

The range of maximum to minimum efficiency is the range within which the remaining systems of the vehicle are constrained – that is, the powertrain system, the wheel-to-road interaction, and the forces necessary to overcome aerodynamic drag.

One of the reasons for the difference in efficiency between the company"X" automobiles and company "Y" automobiles was that the company "X" cars were 1972 models with less stringent means of handling pollution, particularly in the area of exhaust gas recirculation. We believe that if the two engines were equipped with identical devices, the minimum efficiencies could be quite comparable.

The useful power developed by the engine for propelling the vehicle can be further partitioned into that proportion of energy used in overcoming rolling resistance and aerodynamic drag, energy for driving the accessories and auxiliaries, and finally the powertrain transmission losses. Further uses of energy are related to the fuel consumed when the engine is idling, or when the driver accelerates in traversing from one speed to another. In addition, fuel is also consumed in the deceleration process, unless a positive fuel shut-off is effected during deceleration, such as might be found in the fuel injection system. Table 4-10 illustrates the percentage of fuel used for each of the above categories. It also includes data based on operating conditions for the Federal Driving Cycle and for steady-state cruising speeds of 20, 40 and 60 mph. Table 4-11 presents a percentage breakdown of fuel consumption in a vehicle traveling at 20, 40 and 60 mph.

Based on our studies, these tables indicate that the dominant fuel consumption element in the Federal Driving Cycle is rolling resistance which ranges from 23% to 25% for the four vehicles. The rolling resistance is primarily a function of vehicle weight, tire characteristics, and wheel bearings. The rolling resistance is nearly independent of vehicle speed and thus represents a large power-consuming element at low speeds, just the opposite to aerodynamic drag which increases with vehicle speed. Furthermore, as seen in Table 4-7, 60% of the FDC distance is at a near constant speed which is a mode of operation dominated by the rolling resistance. Since the Federal Driving Cycle requires relatively low engine and vehicle speeds, any improvement in rolling resistance will have a marked effect on the fuel consumed during this driving mode. Acceleration energy consumption includes only the energy used for accelerating the inertial load, and represents the second largest energy use during the FDC.

The third major power-consuming element in the federal driving cycle is that attributed to the transmission. This is due to the fact that many part throttle accelerations are experienced in the federal driving cycle which induce relatively high torques and low engine rpm's to the torque converter. The many accelerations experienced in the federal driving cycle thus place a torque demand on the torque converter which forces lower speed ratios in the converter and, subsequently, lower transmission efficiency and higher losses. In essence, the federal driving cycle tests the torque converter stiffness or lack of slip, and relatively high losses in the transmission are found in this mode, depending on the design of the torque converter.

TABLE 4-10

BREAKDOWN OF FUEL CONSUMPTION IN PROPELLING REFERENCE VEHICLES * OVER THE FEDERAL DRIVING CYCLE

Reference Vehicle & Engine Size	Percentage Breakdown of Fuel Consumption						
	Accessory Load	Transmission	Rolling	Aero Dynamic Drag	Acceleration	Deceleration and Idle	MPG
Co Y, 250 CID	11.9	13.9	24.1	13.5	22.6	14.0	13.8
Co X, 400 CID	10.5	13.5	25.5	10.3	16.6	23.6	11.6
Co Y, 350 CID	7.5	16.0	24.3	10.1	20.9	21.2	10.4
Co X, 250 CID	12.8	14.3	23.2	12.2	19.3	18.2	17.5

TABLE 4-11

PERCENTAGE BREAKDOWN OF FUEL CONSUMPTION IN PROPELLING VEHICLE TRAVELING AT 20, 40, 60 MPH (STEADY CRUISE)

Vehicle	Accessories	Transmission	Rolling	Aero Dynamic Drag	MPG
20 mph					
Co Y, 350	19	12	59	10	15.7
Co X, 400	22	16	52	10	16.1
Co Y, 250	22	14	53	11	20
Co X, 250	21	13	55	11	24.9
40 mph					
Co Y, 350	10	14	46	30	18.5
Co X, 400	14	12	44	30	19.8
Co Y, 250	14	12	40	35	20.4
Co X, 250	16	12	40	32	27.1
60 mph					
Co Y, 350	7	12	33	48	15.4
Co X, 400	11	11	38	40	16.5
Co Y, 250	9	10	27	54	16.9
Co X, 250	10	11	28	51	20.7

*Without Air Conditioning.

Accessories account for 10 to 15% of the power consumed in the federal driving cycle and, as would be expected, are higher, percentage wise, at low speeds as opposed to high steady-cruise speeds ranging from 19 to 22% at 20 mph to 7 to 11% at 60 mph. It must be pointed out at this time that the accessory losses are based on all of them operating at peak demand and does not factor in a duty cycle which would depend on the conditions imposed by the driver and the environment.

4.3 THE IDENTIFICATION AND EVALUATION OF INDIVIDUAL FUEL ECONOMY IMPROVEMENTS

4.3.1. Introduction

The approach used for identifying and evaluating the individual improvements for consideration as part of a synthesis vehicle was presented in Figure 2-2 of Chapter II. Since a number of improvement ideas were to be evaluated, we used a step-by-step screening technique which eliminated the least promising at the earliest point in time. It must be understood that every effort was made to get actual experimental test data in order to evaluate an improvement. However, such information, in most cases, was not available (innovators or manufacturers did not have the proper or required data). Therefore, we developed an approach to complete the initial evaluation through interviews, field trips, a literature search, and analytical engineering methods. Figure 4-5 shows graphically how this was accomplished. In addition, a uniform procedure was used to report the results of the total evaluation, including conclusions as to whether or not the improvement should be used in a complete synthesized vehicle system. The following is a general description of this format.

FIVE-STEP EVALUATION FORMAT

Step I – Gives a description of the improvement, its state of development, the principle upon which it is based, and fuel economy and performance information.

Step II – Presents the results of interfacing the improvements with other subsystems and vehicle systems to determine its compatibility with either functional requirements, e.g., space and geometry, thermal and cooling system, and mechanical and electrical subsystems.

Step III – Identifies and explains the constraints with which the improvement would not comply.

Step IV – After passing the previous criteria, evaluates improvement further on basis of remaining program objectives, i.e., costs, logistics, operational requirements, time scale, and user acceptance.

Step V – Presents conclusion relating to its acceptability for use in a synthesized vehicle design.

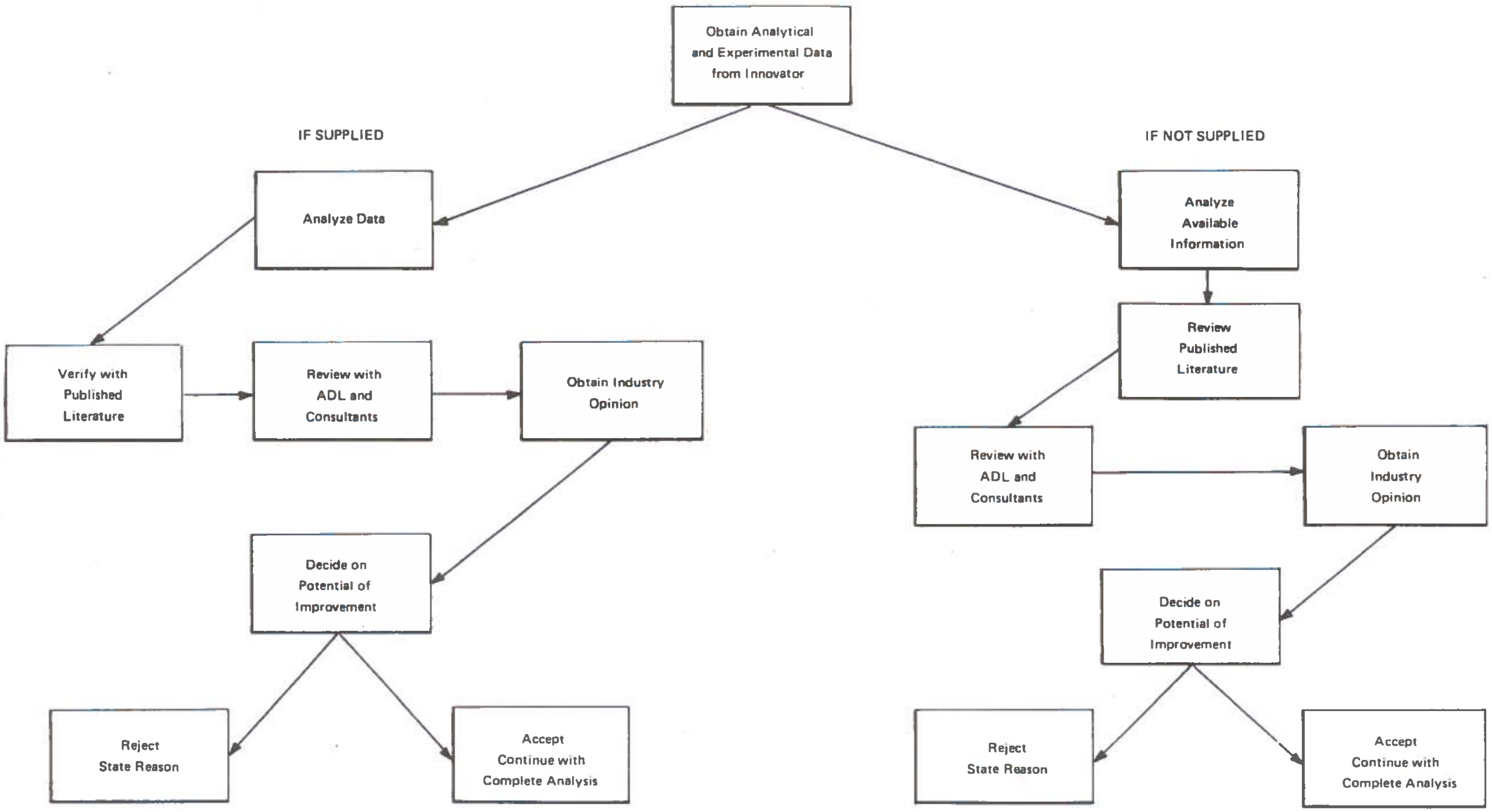

FIGURE 4–5 INITIAL SCREEN IMPROVEMENT IDEA

4.3.2. Background to Principles of Engines Considered

Exploring the innovations of automobile powerplants can lead to an unending list of conceivable improvements. However, all powerplants are governed by some basic thermodynamic relationships. In the following paragraphs, these relations will be developed to investigate the possible innovations which could improve the efficiency of present or near-term alternative automobile powerplants. It is important to consider engine improvements from such a fundamental standpoint, to treat adequately the myriad of possible design improvements which can be utilized.

The indicated horsepower is the power delivered by the combustion of the air/fuel mixture in the cylinder to the piston. The indicated power is then transmitted by the piston rod to the crankshaft where it becomes useful brake horsepower. The governing equation for the horsepower output of an engine is given in Equation (4-1).

$$\text{I H.P.} \propto \dot{W}_a A \eta_i \qquad (4\text{-}1)$$

where:

I H.P. = indicated horsepower
$\dot{W}_a$ = flow rate of air
η_i = indicated thermal efficiency, and
A = air/fuel ratio

Equation (4-1) shows that the indicated horsepower depends on the flow rate of air, the air-to-fuel ratio, and the indicated thermal efficiency. In an ideal engine cycle where the air fuel mixture ratio is maintained at stoichiometric which for common fuels is approximately 14.7, the indicated thermal efficiency η depends primarily on the compression ratio r . This relationship is shown in Equation (4-2). For gasoline engine.

Ideal "Air" Cycle

$$\eta_i = 1 - \frac{1}{r^{k-1}} \qquad (4\text{-}2)$$

where:

r = compression ratio
k = the adiabatic expansion coefficient, about 1.4 for air

Plotting typical experimental data for various compression ratios, it may be seen in Figure 4-6 that the thermal efficiency of the engine increases as the compression ratio increases. Since the fuel delivered to the cylinder is the product of the air/fuel ratio and the flow rate of air, then the amount of fuel consumed per indicated horsepower per hour output is inversely proportional to the thermal efficiency as shown in Equation (4-3).

Indicated Fuel Consumption (4-3)

$$\text{ISFC} \propto \frac{1}{\eta_i}$$

where:

ISFC is the fuel consumption per indicated horsepower per hour or indicated specific fuel consumption.

This quantity is called the indicated specific fuel consumption. It is a measure of the fuel economy of the power plant which must deliver horsepower by consuming fuel. Therefore, as one would expect, the thermal efficiency of the engine determines the fuel economy based on indicated horsepower. Since for an ideal engine the indicated thermal efficiency is a function of the compression ratio alone, the amount of fuel consumed for each indicated horsepower will decrease as the compression ratio increases. The effect of compression ration of a gasoline engine on Equation 4-2 is shown in Figure 4-6. The ideal engine thermal efficiency represents the thermodynamic limit of efficiency of an engine.

In reality, however, the thermal efficiency depends on more than just the compression ratio. The indicated thermal efficiency depends on a variety of factors, some of which are the air/fuel mixture ratio, the amount of exhaust gas recirculation, ignition timing, heat losses, gas blowby and the heat capacity of the mixture. The combined effect of compression ratio and the addition of real fuel and air conditions is also shown in Figure 4-6. The change in thermal efficiency from the ideal case to the real is due to the energy losses associated with real combustion processes. Some of the heat which goes into work in the ideal cycle goes into heating the gas mixture in the cylinder which is then exhausted carrying with it energy. Incomplete combustion due to poor fuel distribution is also experienced resulting in further loss in efficiency. As the amount of the air-to-fuel ratio* changes, these energy loss effects alter the engine efficiency. The influence of the air/fuel ratio can be seen more clearly in Figure 4-7 which shows the indicated thermal efficiency at a fixed compression ratio. A change in the air/fuel ratio from 16.67/1 to 12.50/1 can lower the thermal efficiency by almost 30% which leads to a substantial increase in the specific fuel consumption. The ignition timing, heat loss, and gas blowby effects on the thermal efficiency are real but somewhat smaller and can be more difficult to assess. However, they should not be discarded since real attempts at improving the thermal efficiency by optimizing the ignition timing, heat loss and lowering the gas blowby have been made.

The delivery of real horsepower (called brake horsepower [BHP]) by the powerplant for useful propulsion of the vehicle is governed by the friction horsepower (FHP) as shown in Equation 4-4.

Actual Horsepower (4-4)

$$\text{B.H.P.} = \text{I.H.P.} - \text{F.H.P.}$$

where:

B.H.P. = the useful power of brake horsepower
F.H.P. = the engine friction horsepower

To increase the useful power delivered by the power plant the friction horsepower should therefore be minimized. The friction horsepower can be divided into two parts: pumping losses and mechanical losses. The mechanical losses are associated with the friction of the piston in the cylinder and bearing losses. The pumping losses are the added inefficiencies caused by restricting the flow of the air/fuel mixture by purposely throttling the intake manifold for power control, which results in a partial vacuum in the combustion chamber while the pistons pump against the

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* The stoichiometric air/fuel ratio is that ratio at which the number of oxygen molecules in the mixture is just sufficient to burn up the fuel molecules present.

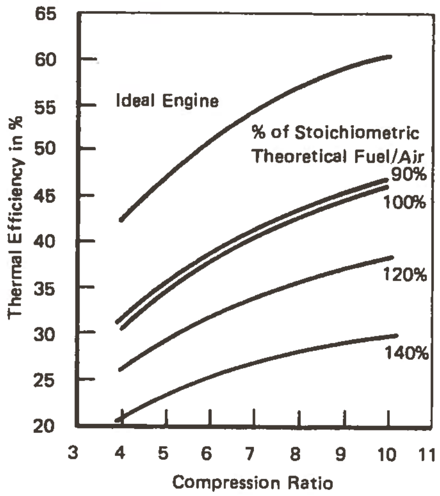


FIGURE 4–6 THE EFFECT OF COMPRESSION RATIO ON THE EFFICIENCY OF THE CONSTANT-VOLUME FUEL-AIR CYCLE WITH $p_{ex} = p_i = 14.7$ PSIA, $T_i = 520^\circ R$

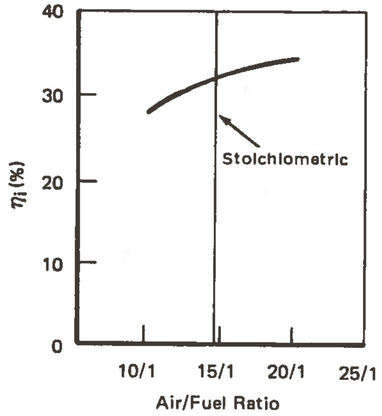
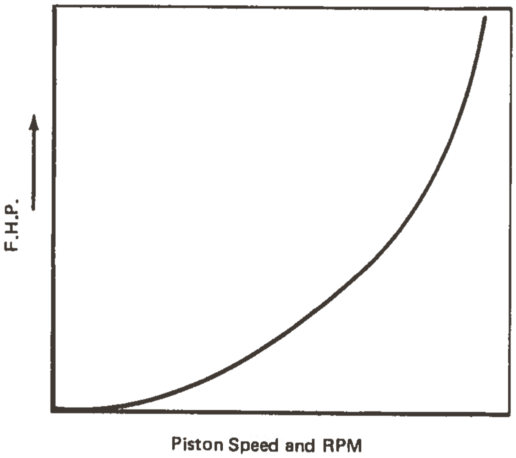


FIGURE 4–7 EFFECT OF AIR/FUEL RATIO ON INDICATED THERMAL EFFICIENCY η_i AT FIXED COMPRESSION RATIO r



Source: Rogowski; A.R. Elements of Internal Combustion Engines, McGraw-Hill, 1953

FIGURE 4–8 EFFECT OF PISTON SPEED ON FRICTIONAL HORSEPOWER (F.H.P.) AT FIXED COMPRESSION RATIO r atmospheric pressure of the crankcase or by restrictions caused by the configuration and length of the manifold. In order to maximize the brake horsepower output, therefore, the mechanical losses and pumping losses must be minimized. In internal combustion engines the mechanical and pumping losses increase with the piston speed of the engine. Figure 4-8 shows the effect of piston speed (proportional to RPM) on frictional horsepower.

Therefore the factors affecting the fuel economy of the power plant are divided into two classes; those affecting the thermal efficiency and those affecting the friction horsepower. Table 4-12 displays the general approaches which may be taken to improve indicated thermal efficiency and reduce frictional horsepower. These individual approaches may be combined into an engine concept. Table 4-12 also shows how various piston engine concepts such as lean burn, stratified charge, and diesel engines may be categorized.

4.3.3. Powerplants

Because of the immediacy of the fuel shortage, the need for a near-term solution for fuel economy gains dictated that solutions be developed from an existing base of technology and industrial production capability. Of all the constraints discussed early in this report, the most important ones to consider when examining powerplants are the potential for fuel economy improvement and the evolutionary timetable to produce a mass-producible engine at the earliest date which is least disruptive to the industry and the nation's economy. The study of opportunities for near-term improvement of the fuel economy of the present spark-ignition, naturally aspirated piston engine started by reviewing existing powerplants used in mass-produced, light-duty passenger vehicles today, and those concepts which appear to have satisfied the opportunities outlined in the basic principles and proposed improvements shown in Table 4-12. Each of these concepts assumes that optimum intake manifold and exhaust system design would be incorporated to reduce flow losses, and also, that the present trend toward the use of high-energy, sustained electronic ignition systems would continue. The naturally aspirated spark-ignition engines considered are:

- the standard engine with optimum spark setting, improved carburetor, catalytic converter, and EGR;
- the lean-burn engine utilizing lean carburetion or electronic fuel injection techniques, and possibly including a catalytic converter and EGR; and
- the stoichiometric air/fuel ratio engines using closed-loop fuel control systems and three-way catalytic converters.

These three approaches will be discussed in detail in the following section. Additional engines which were examined as having favorable potential were:

- turbo-charged spark-ignited engine,
- stratified-charge engines, and
- diesel four-stroke engines.

TABLE 4-12

GENERAL APPROACHES TO IMPROVING THERMAL EFFICIENCY AND REDUCING FRICTIONAL HORSEPOWER

Improvements Aimed at an Increase in Indicated Thermal Efficiency

Increase Compression Ratio

- Leaded fuel for spark ignition engine
- Stratified charge engine
- Diesel

Optimize Air/Fuel Ratio

- Lean burn spark ignition engine
- Stratified charge (PROCO) (TCCS)
- Dual-chamber stratified charge
- Diesel
- Stoichiometric A/F with closed-loop-emission-control system and catalyst
- Optimized spark setting with catalyst and improved carburetor

Ignition Optimization

- Optimize spark advance
- High energy spark
- Sustained ignition
- Wider gap

Improved Air/Fuel Cylinder-to-Cylinder Distribution & Reduced Cycle-to-Cycle Variation

- Improved manifold design
- Higher intake air temperature
- Increase intake air turbulence

Improvements Aimed at a Decrease in Frictional Horsepower $\frac{\text{F.H.P.}}{\text{WaF}}$

Increase Air Capacity

- Improved exhaust and intake manifolding for spark ignition engine
- Turbo- or supercharged engine

Decrease Mechanical Friction

- Piston ring modification
- Lower engine speed requirement by a wider range of gearing in the transmission
- Improved lubricants

Decrease Pumping Losses

- Turbocharged or supercharged engines
- Operate engine under less throttled conditions by proper engine and transmission matching, e.g., greater range of gearing or continuously variable transmissions
- Eliminate throttling by use of diesel

Other powerplant concepts were considered but because they did not satisfy the constraints of this study they were not evaluated; however, further evaluation is in order for possible long-term benefits. The powerplants in this category are:

- two-stroke engines,
- rotary engines (spark-ignited, stratified charge or diesel),
- gas turbine engines,
- Rankine cycle engines,
- Stirling engines, and
- electrically powered automobiles.

An evaluation of the technical improvements prepared for each powerplant, as measured against the program constraints, is presented in the following subsections.

4.3.3.1. Modified Conventional Engine Equipped with Oxidation Catalyst, Improved Carburetor or Fuel Injection System, and Optimized Spark Timing

This system is essentially the same as the engines used in the 1973-1974 automobiles with the exception that each engine will be equipped with exhaust system devices that will adequately reduce the pollutants while allowing the engine to be run at a more efficient spark timing setting. This modification will result in fuel economy gains of approximately -5 to 10% measured in miles per gallon, depending on specifics of the system each manufacturer uses. Table 4-13 presents a comparison of the approaches being taken by General Motors, Ford, and Chrysler. This information appeared in the April 15, 1973, issue of Automotive Industries before the 1976 interim standards had been established, and indicates, in general, the approaches being taken for 1975 models. Improvements are constantly being made. However, for proprietary reasons future improvements were not disclosed. Therefore, we feel that it will be possible to improve the fuel economy shown in the table by a maximum of 10% by means of spark advance.

The devices used to clean up the pollutants will vary in construction with manufacturers, but all will use an oxidation catalyst. All the concepts will involve: exhaust gas recirculation and the use of air pumps, improved ignition, improved carburetion to provide more accurate fuel metering with compensation for air density changes, and finally an electrically powered choke that cuts back quickly at ambient temperatures greater than 70°F. The system will feature:

- A quick heat intake manifold designed to promote rapid fuel evaporation after engine startup,

- An electronic ignition systems to eliminate the wear and other problems associated with present distributors,

TABLE 4-13

COMPARISON OF BIG THREE 1975 CATALYTIC CONVERTER SYSTEMS

	General Motors			
	Underfloor	**D-MEC***	**Ford**	**Chrysler**
Catalyst Material	Platinum & Palladium	Platinum & Palladium	Platinum & Palladium	Platinum & Palladium
Amount of Catalyst (Troy oz.)	.005-.10 Pt. .02-.075 Pd.	.005-.10 Pt. .02-.075 Pd.	.07-.10 Pt. .006-.05 Pd.	Less than 0 1
Catalyst Volume (cubic inches)	160 (4,6) 260 (V-8)	60	75 (4,6) 102 (small 8) 150 (large 8)	135
Substrate	Pellets	Monolith or Pellets	Monolith	Monolith
No. per car	1	1	2 (V-8)** 1 (4,6)	1
Location	Underfloor	Manifold	Toeboard	Underfloor
Converter Protection	Undetermined	By-pass above 1500-1700° or above 60 MPH	Air cut off at 1700°F.; EGR & air cut off at 64 MPH	Overtemp. Warning
Projected Fuel Economy Vs. '73	No change[†]	No change	Down 5%	Down 5%
Initial Retail Cost over Uncontrolled car	$250-$315		$383	$363
Initial Retail Cost over 1973 car	$275		$303	$262***

*Dual Mode Emission Control

**One converter on Maverick, Comet, Econoline and Bronco

† Based on our discussions with this industry, ADL feels that a more realistically projected fuel economy improvement is possible, and we have therefore used a maximum of 10%.

Source: Automotive Industries, April 15, 1973

- An exhaust gas recycling line and control valve to hold the NO_x emissions below 3 gm/mile by recycling about 10% of the exhaust gases.

- An air pump to inject air into the exhaust ports to oxidize the carbon monoxide and hydrocarbons.

- A catalytic converter in the exhaust system to promote further oxidation of the hydrocarbons and CO.

Figure 4-9 shows Ford's proposed 1975 emission control system, Figure 4-10 shows Chrysler's catalyst location, and Figure 4-11 shows GM's Manifold 1975 emission control system.

According to the National Research Council, the technological risk appears to be relatively low for this concept; however, there is concern about the effect of improper engine maintenance on the catalytic converter and thus on emission control. Presently, there are no data concerning the deterioration of emission control systems under conditions of customer use. Since vehicles utilizing the system will have to be certified for the 50,000-mile durability test, there must be some assurance that the vehicles will be properly maintained, as prescribed, when in the hands of the public. Therefore, we feel that unless a rigid inspection system is implemented, the systems will be operating less efficiently than originally intended. Table 4-14, taken from a report by the National Research Council,[15] illustrates the technical improvements developed by the automobile manufacturers which ultimately will lead to the concept described. The report included very thorough estimates of the added costs for the introduction of these devices to the modified standard car. For 1975 the estimate showed an increase in the sticker price of $138.20 to the purchaser from 1970 to 1975. This increase was based on 1972 dollars. Table 4-15 shows a cumulative price through the years amounting to a total or cumulative cost to the consumer by 1976 of $392.80 for all emission control devices added from 1966. While the manufacturability of the various parts in the system is such that they can be mass-produced in enough volume to satisfy in aggregate the expected demand for vehicles in the '75 and '76 models, there is some question about maintenance and durability, and the least durable portion of the system is the catalyst. The catalyst is exposed to repeated cycles of heating and cooling, evaporation and condensation of water, pulsating flow from exhaust gases, vigorous shaking on the road, and a variety of poisons including lead and sulfur from the fuel, spark plug misfiring, sustained operation at high engine power and descent down long hills. These are some examples of situations that could result in the catalyst overheating and possibly failing.

Furthermore, there is no incentive to the driver to maintain the system since, in some cases, the automobile will operate more efficiently if the systems are malfunctioning. For instance, stoppage of the EGR system could actually improve gas mileage while increasing the NO_x permitted. Recently General Motors' engineering staff has shown that EGR, properly proportioned to engine load can possibly improve fuel economy.[16]

These systems will also require higher engine operating temperatures which could result in possible failure of materials in the engine compartment due to the higher temperature.

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[15] Committee on Motor Vehicle Emissions, Division of Engineering, National Research Council, in accordance with Section 202 (C) of the Clean Air Amendment of 1970, by the National Academy of Sciences, February 12, 1973.

[16] Gumbleton J.J., Bolton R.A., Lang H.W. optimizing engine parameters with exhaust gas recirculation SAE 470104 Feb. 25 –March 1, 1974.

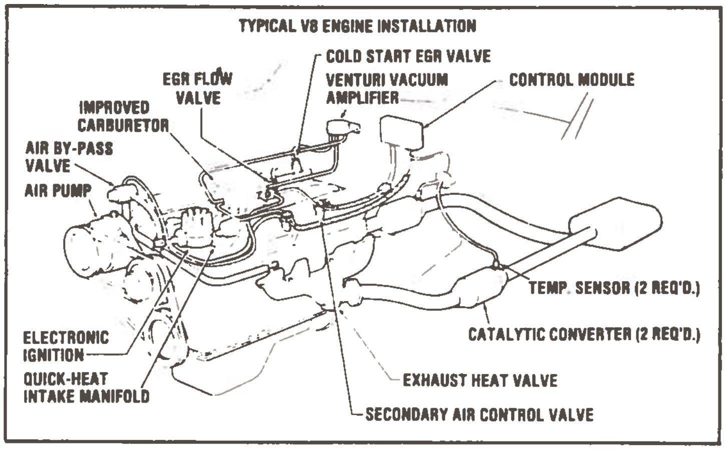

FIGURE 4–9 PROPOSED 1975 EMISSION CONTROL SYSTEM – FORD

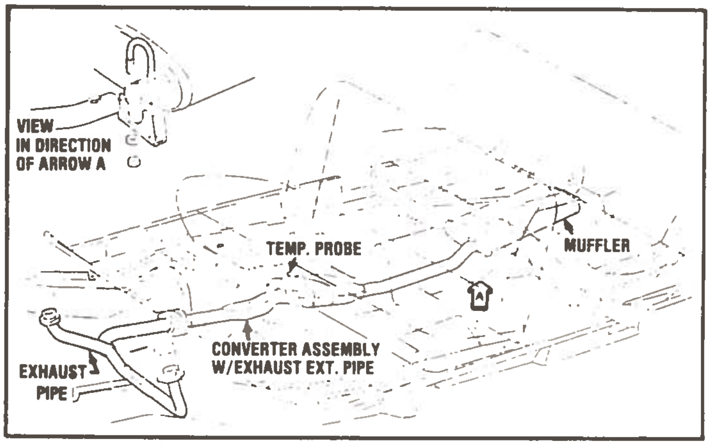

FIGURE 4–10 PROPOSED CATALYST LOCATION – CHRYSLER

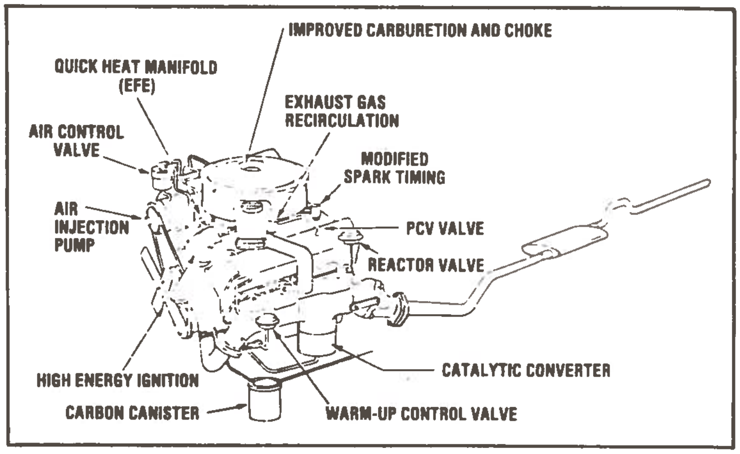

FIGURE 4–11 PROPOSED MANIFOLD 1975 EMISSION CONTROL SYSTEM – GM

Source: Callahan, J.M., "Catalytic Converters: Will the Seed Money Pay Off?" *Automotive Industries*, April 15, 1973.

TABLE 4-14

CHRONOLOGY OF DEVELOPMENT OF THE DUAL-CATALYST SYSTEM

Model Year	Emission Hardware Added
1966	a) PCV Valve
1968	a) Fuel-Evaporation Control System
1970	a) Retarded Ignition Timing
	b) Decreased Compression Ratio
	c) Increased Air/Fuel Ratio
	d) Transmission-Control System
1972	a) Anti-Diesel Solenoid Valve
	b) Thermostatic Air Valve
	c) Choke-heat Bypass
1973	a) Exhaust-Gas Recirculation
	b) Air-Injection Reactor
	c) Induction-Hardened Valve Seats
	d) Spark Advance Control
	e) Air Pump
1974	a) Precision Cams, Bores, and Pistons
	Emission Hardware-Likely Configuration
1975	a) Proportional Exhaust-Gas Recirculation
	b) Carburetor with Altitude Compensation
	c) Air/Fuel Preheater
	d) Electric Choke
	e) Electronic Ignition
	f) Improved Timing Control
	g) Oxidizing Catalytic Converter
	h) Pellet Charge
	i) Increased Cooling System
	j) Improved Underhood Materials
	k) Body Revisions

Source: Developed from Report by The Committee on Motor Vehicle Emissions, National Academy of Science, Washington, D.C., February 1973.

TABLE 4-15

SUMMARY OF STICKER PRICES FOR EMISSIONS HARDWARE FROM 1966 UNCONTROLLED VEHICLE TO 1976 DUAL-CATALYST SYSTEM

Year	Sticker Price Increase	Cumulative Price
1966	$ 3.00	$ 3.00
1968	15.00	18.00
1970	8.00	26.00
1971-72	14.00	40.00
1973	60.00	100.00
1974	20.60	120.60
1975	138.20	258.80

1972 Dollars

Source: Report by The Committee on Motor Vehicle Emissions, National Academy of Science, Washington, D.C., February 1973.

We have included this approach since the automobile manufacturers are well down the road in implementing the application of these devices.

In regard to the availability of materials the catalyst will require noble metals, such as platinum and palladium, which have to be imported from foreign countries.

We were unable to obtain engine performance information which would permit us to simulate fuel economy gain; however, in talking with automobile manufacturers we were told that improvements as great as 15% could be realized because of improved carburetion and optimized spark timing. However, being conservative we estimated a 10% improvement for our cost saving calculation. We were requested not to disclose the confidential nature of the information received from various manufacturers.

4.3.3.2. Lean Burning Spark Ignition Engines

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.[17],[18] As a

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[17] Hansel, J.G., Lean Automotive Engine Operation – Hydrocarbon Exhaust Emissions and Combustion Characteristics, SAE Paper No. 710161, January 1971.

[18] Hirschler, D.A., Adams, W.E., and Marsee, F.J., Lean Mixtures, Low Emissions, and Energy Conservation, Paper AM-73-15, National Petroleum Refiners Association, NPRA Annual Meeting, April 1973.

result, there is a potential 15-20% fuel economy improvement available from lean operation, providing the compression ratio is increased, the ignition system optimized, and a thermal reactor is used. Hirschler,[18,19]* Lindsay,[20] Hansel,[17] and Rivard[21] all discuss the virtues of lean operation as a means of reducing both exhaust emissions and fuel consumption. Lindsay [20,22] provides a particularly good description of the benefits available from homogeneous mixtures and lean operation. Specifically we wish to direct the reader to information contained in the appendix on these concepts.

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.

The limit to which this can be practically achieved is constrained by the driveability of the car during part throttle operation. The problem areas in driveability are stumble, surge, and stalling caused by erratic firing or misfiring. This condition first appears in the cylinder which has the leanest mixture. The problem areas to be overcome in the lean air/fuel combustion process are initial and sustained burning of the lean mixture and the cylinder-to-cylinder and cycle-to-cycle variations in the air/fuel ratio. The basic advantage inherent with this concept is the chance for success in the near term, since it is readily adaptable to present conventional engines, and the cost is low.

Generally it can be said (see Table 4-16) that a 5 to 15% improvement in fuel consumption can be achieved. Engineering tests and analysis have shown that when the air/fuel ratio is approximately 18/1 to 20/1, the emission of NO_X HC, and CO is at the lowest level as a group (see Figure 4-12). It is particularly important to note that the NO_X is the most difficult emission to control without degradation of engine efficiency and the most difficult to eliminate once formed. The improvement can be accomplished by several different techniques in combination with one or more of the following:

1. Air management – assuring that the distribution of air and fuel is as near equal for each cylinder through improved intake and exhaust manifoldings;

2. Improved fuel atomization fuel control through improved carburetion, or ultrasonic break up of fuel particles;

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[19] Hirschler, D.A., and Marsee, F.J., Meeting Future Automobile Emission Standards, Paper AM-70-5, National Petroleum Refiners Association, presented at Annual Meeting, April 1970.

[20] Lindsay, R., Heat Pipe Vaporization of Gasoline – VAPIPE, paper presented at CCMS Conference, Ann Arbor, Mich., 14-19 October 1973.

[21] Rivard, J.G., Closed-Loop Electronic Fuel Injection Control of the Internal-Combustion Engine, SAE Paper No. 730005, January 1973.

[22] Lindsay, R., Thomas, A., Woodworth, J.A., and Zeschmann, E.G., Influence of Homogeneous Charge on the Exhaust Emissions of Hydrocarbons, Carbon Monoxide, and Nitric Oxide from a Multicylinder Engine, SAE paper 710588, 1971.

* Hirschler, D.A., letter to Dr. Emerson Pugh, Dated 3/28/74; also see Appendix III, Section 1, Page 30.

3. Timed sequential fuel injection;

4. Wider spark plug gap, increased spark intensity and duration to assure initial and sustained burning of mixture;

5. Intake air heating to assure better vaporization of fuel and homogeneity of mixture;

6. Intake valve throttling to increase turbulence in combustion chamber;

7. Combustion chamber modifications, sometimes made to introduce an additional spark plug or to further enhance the complete burning of the lean air/fuel mixture;

8. Use of gaseous fuel additions to the air/fuel mixtures to improve driveability. (This concept was not considered within the scope or time frame of this case.)

The technology is well understood and a number of high grade companies are developing different technical improvements.

During the course of this study we made contact with several companies involved in development activities on lean burning engines:

Company	Device
Ethyl Corporation	Lean carburetor w/manifold thermal reactor
Bendix Corporation	Electronic fuel injection
Shell International Petroleum Co., Ltd.	"Vapipe" – vaporizing carburetor
Dresser Industries, Inc.	"Dresserator" – variable Venturi carburetor
Autotronic Controls, Inc.	Ultrasonic atomizer with precise electronic fuel/air metering
General Motors Corporation	Intake valve throttling by means of variable valve lift
Jet Propulsion Labs, Pasadena, California	Hydrogen spiking of air/fuel mixture – in early development

Field trips were made to Ethyl, Bendix, Dresser and Autotronic Controls whereas Shell and G.M. were handled with personal contacts and information from published technical papers. The salient points and general conclusions regarding each of these devices are listed and compared in Table 4-16. Some schemes enjoy a greater measure of success in achieving these features than others. Insufficient technical data were available to allow an accurate quantitative comparison of these various lean burning schemes. None of the companies contacted was able to provide enough technical data to allow a computer simulation run for evaluation of potential fuel savings. However, Ethyl, Shell, and Dresser were able to provide comparative test data for fuel economy and

TABLE 4 16

SUMMARY OF LEAN BURNING ENGINE DEVELOPMENTS INVESTIGATED

Developer	Device/Description	Reference	Emissions Capability	Fuel Economy Improvement	Problem Areas	State of Development	Data Availability	Durability, Reliability, Repairability	Added Initial Cost To First Owner
1. Ethyl Corporation Automotive Research Laboratory Detroit, Michigan	High velocity — variable venturi Carburetor set for lean mixtures. Also includes 1. Manifold reactor 2. Exhaust port inserts for heat retention 3. Modulating EGR 4. Modified ignition timing	18,19,23*	Close to goals of this study	About 10%	• Does not quite meet emissions targets on HC, CO	Prototype devices evaluated proving concept works well, high chance of success.	Data indicates that concept should be developed further.	Should be comparable to present equipment.	$80 – $100
2. Bendix Research Labs Southfield, Michigan	Electronic Fuel Injection Timed pulse fuel injection behind intake valves — combined with electronic control of fuel/air ratio; — high intensity electronic ignition	21,24,25, 26	Close to goals of this study	About 5-10%	Fuel metering more complex than carburetion and hence less reliable, repairability costly.	Has performed development evaluation, hardware available.	Limited data available, tends to indicate that gains over other systems would not justify added costs.	Capable of being developed to be comparable to present systems.	$125 – $225
3. Dresser Industries, Inc. Santa Ana, California	"Dresserator" — high-velocity variable venturi carburetor with unique fuel metering method; developer claims — • Better air/fuel ratio control • Smaller droplets, narrow size distribution • Better A/F accuracy over wide turndown Used with EGR and manifold reactor	27	Close to goals of this study Present H.C. 8-1.0 gm/mi CO 4.-6 gm/mi NO_x 1.0-1.6 gm/mi	5-15% over FDC, no steady speed data	• Manufacturing cost Time for development and actual gains not possible to estimate. • Feasibility of production design not established.	In process of developing feasibility model into prototype for testing and evaluation. Developers feel that manifold changes will result in emissions being met.	1. Incomplete data. 2. Because of confidential nature, could not investigate hardware, however, principle of operation is valid.	Unknown.	Said to be comparable to present systems. But seems doubtful.
4. Autotronic Controls Corporation El Paso, Texas	Electrosonic III-lean burning fuel delivery system consisting of an ultrasonic fuel atomizer, accurate turbine-type air flow meter and "Digipump" fuel proportioning pump with electronic controls integrating all components into a system for precise air/fuel ratio control.	28,29	No reliable emissions data available yet.	Estimate about 5% improvement.	Fuel and air metering and controls more complex than present system, may require periodic calibration.	Semi-production items available, must be optimized for mass producibility.	• Lack of good test data for proper evaluation of this system, automobile industry is testing units.	Complexity adds to possible repair costs; durability and reliability not proven but should be acceptable.	$50 – $75
5. General Motors Corp. Detroit, Michigan	Intake valve throttling (IVT) by means of variable intake valve lift — combined with fuel injection behind intake valves; intense, high-velocity mixture over entire load range provides good fuel atomization and allows operation at lean A/F ratios.	30	No data available on emissions	Provides up to 20% improvement in BSFC at light load; no data available on economy over driving cycle.	• Mechanical complexity; control mechanism for variable valve life appears limited, electronic fuel injection system must be developed to optimize concept.	Feasibility studies only, no hardware available.	Data source indicates maximum possible gain of all concepts.	Durability not yet proven, electronic fuel-injection systems add complication, reduce reliability and repair cost.	$150-$250
6. National Engineering Laboratory, Shell International Petroleum Co., Ltd. London, England	"Vapipe" — vaporizing carburetor employs conventional carburetor followed by a heat pipe device utilizing exhaust manifold heat to vaporize fuel in mixture; provides homogeneous mixture to all cylinders and allows lean operation up to A/F ratio of 20.	20,22	Nearly meets 1975 standards but does not yet appear to reach emission goals of this study.	8-10% at steady speed; shows 20-40% improvement over FDC (results questionable).	• Substantial power loss due to fuel vaporization and mixture preheating; • Cold start difficulties with high emissions and fuel consumption during warmup. • Cost and manufacturing problems.	Feasibility hardware only.	Very limited fuel usage and performance data available; good gains indicated.	Hardware not proven boiler inserted into exhaust system subject to possible short life.	Not known probably $50-$100
7. Jet Propulsion Laboratory, Pasedena, California	Spiking fuel mixture with hydrogen	31	Should meet goals of study. However cold starts may be a problem.	Very limited indications; good engine fuel usage gains would be partially offset by energy loss due to generation of hydrogen gas.	Feasibility studies only.	Complete development required; probably not within time-frame of case.	Very limited	Not known	Not known

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23. Eltinge, L., Marsee, F.J., and Warren, A.J., Potentialities of Further Emissions Reduction by Engine Modifications, Paper presented to SAE Congress, January 1968.
24. Keranen, T.W., and Wertheimer, H.P., Spark Ignition Engine Control Variables Study, SAE Paper No. 730004, January 1973.
25. Davis, C.W., *et al.* Fuel Injection and Positive Ignition — A Basis for Improved Efficiency and Economy, SEA Paper No. 190A, Chicago Summer Meeting, June 1960.
26. Zechnall, R., Baumann, G., and Eisele, H., Closed Loop Exhaust Emission Control System with Electronic Fuel Injection, SAE Paper 730566, May 1973.
27. News Release "Dresser Announces Signing of Agreement with Ford on New Auto Emission Control System," June 21, 1973. Dresser Industries Inc., Dallas, Texas. (See Appendix III, Section 1, Page 30.) For Additional Claims Made by Developer, Dated 8/10/74.
28. Product Bulletin ACO127 and APD200, Autotronic Controls Corporation, El Paso, Texas.
29. Product Bulletins, 100A1, 100B1, 100C1, 100D1, Autotronic Controls Corporation, El Paso, Tx.
30. Stivender, D.L., Intake Valve Throttling (IVT) — A Sonic Throttling Intake Valve Engine, SAE Paper No. 680399, May 1968.
31. Breshears, R., Cotrill, H., Rupe, J., Partial Hydrogen Injection into Internal Combustion Engines, Effect on Emissions and Fuel Economy, Oct. 14-19, 1973 Ann Arbor, Mich.

*Hirschler, P.A. Letter to Dr. Emerson Pugh, March 28, 1974, also see Appendix III, Section 1 emissions over the FDC or during city/suburban driving. They typically compared vehicles equipped with their devices against 1973 model production automobiles. These companies, where possible, provided vehicles equipped with their technical improvement for our qualitative evaluation. All the vehicles performed in a reasonable manner; however, each requires further development before mass production is possible. Because of the current state of development, adequate amounts of actual experimental data were not found available. Thus a thorough analytical appraisal to determine fuel usage could not be made.

The general ADL overall conclusion is that a fuel economy increase of between 5 and 10% can be expected from these lean-burning engines compared with 1973 model year cars, while simultaneously achieving the emissions targets of this study. Further perhaps as much as 5% gains in fuel economy may be achieved if compression ratio were increased. This would require higher than 91 octane fuel. We did not include this possibility for this study.

One outstanding deviation from this estimated improvement occurs in the data reported by Shell for the "Vapipe" system[16] where they show a 20-40% economy gain over the U.S. federal driving cycle and a similar gain for European and Japanese urban driving cycle tests. Since these results are clearly at variance with those from all other lean combustion schemes, the authors must question the validity of the Shell test results. One question that seems appropriate to raise is whether or not the "Vapipe" tests were based on a cold start procedure as required for emissions certification. It is also appropriate to ask whether their reference vehicle before modification represented good conventional carburetion practice, and how much improvement resulted merely from replacing a less than optimum carburetor. Time did not permit a thorough investigation of this early experimental device.

As the development of these different concepts matures further validation will be required to determine their worthiness. These devices also appear to have the advantage of lower maintenance requirements with less incentive offered for owners to tamper with emission control devices. If emission controls do not become more stringent than the interim '76 standards, one or more of these lean burning techniques is likely to be introduced into production.

The estimated earliest implementation date is 1977 and the probable chance of success is high.

4.3.3.3. 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. No data are available for computer simulation. 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 have indicated in the previous section 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 stoichiometric, e.g., a 19:1 air/fuel ratio or more (Figure 4-11). 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.[32,33] * If the compositions of exhaust gases going to a dual-purpose catalyst or so-called three-way catalyst (see Figure 4-13) 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 (Figures 4-14 and 4-15). 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.

A number of large companies have been working on systems to accomplish this – Bendix,** Universal Oil Products,*** and Robert Bosch† to name a few – with what has been reported to be a high degree of success. 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 composition 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. A simplified schematic of this system is shown in Figure 4-16.

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32. Bond, J., Controlling Emissions Automotive Industries, 1 November 1973.

33. Reddy, J.N., Closed-Loop Emission Controls for Automotive Engines, Bendix Technical Journal, Spring 1973.

* Also discussions with Universal Oil Products and Bendix Corporation personnel.

** Bendix Corporation, Electronic Fuel Injection Division, Troy, Michigan, and Bendix Research Laboratories, Southfield, Michigan.

*** Universal Oil Products Co. (U.O.P.), Automotive Products Division, Des Plaines, Illinois.

† Robert Bosch, GMBH, Stuttgart, Germany.

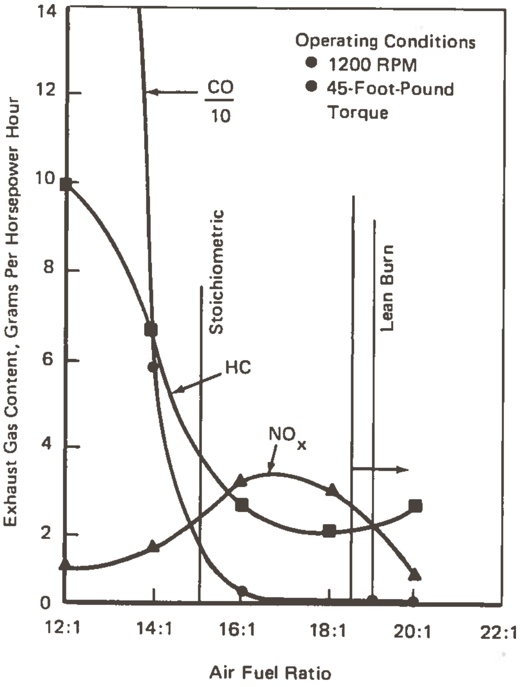


FIGURE 4–12 **EFFECT OF AIR/FUEL RATIO ON EXHAUST-GAS CONTENT**

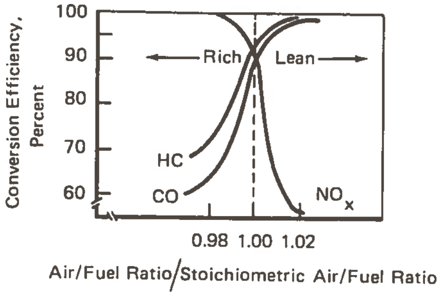


FIGURE 4–13 **EFFECT OF AIR/FUEL RATIO ON CONVERSION EFFICIENCY OF DUAL-PURPOSE CATALYST**

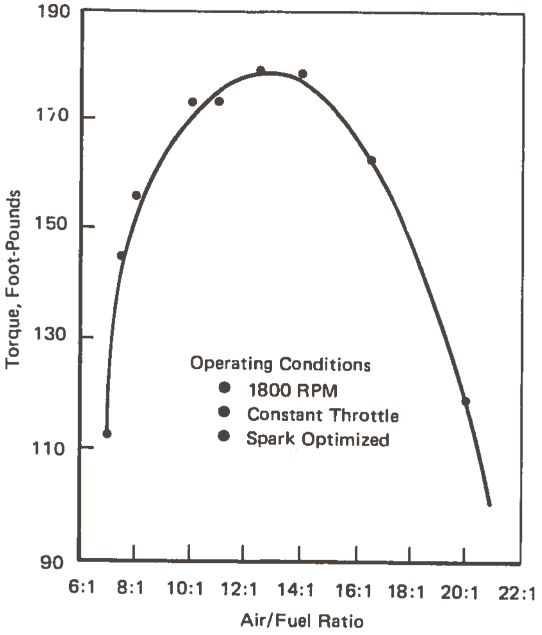


FIGURE 4–14 **EFFECT OF AIR/FUEL RATIO ON ENGINE TORQUE**

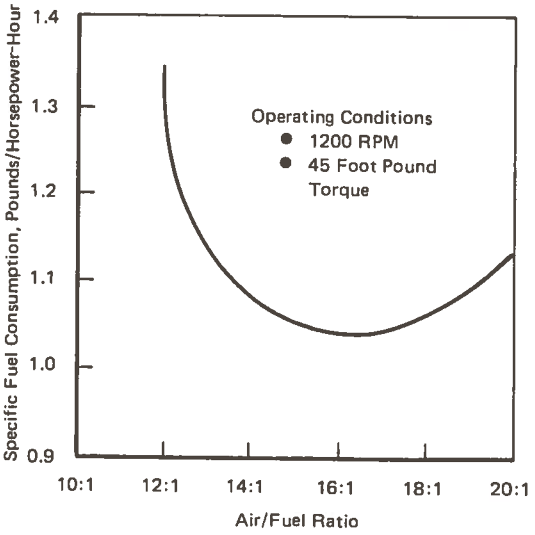


FIGURE 4–15 **EFFECT OF AIR/FUEL RATIO ON SPECIFIC FUEL CONSUMPTION**

Source: Reddy, J.N., "Closed Loop Emission Control for Automotive Engines," *Bendix Technical Journal*, Spring, 1973.

While we were unable to obtain experimental data on fuel economy or performance data from the various developers contacted, we were assured that tank mileage improvements ranged from 12% to 25% over 1973 fuel economy without performance penalty. This appears possible providing the engine is, in fact, set to run at stoichiometric, optimum spark timing, and with minimum exhaust gas recirculations.

The present state of development of the Bendix, U.O.P., and Bosch systems appears to be well past the feasibility stage. Apparently one of the technical problems that has to be solved is the development of a low-cost and reliable oxygen sensor which can approach the durability associated with automotive components operating in a hostile exhaust gas environment. Figure 4-17 shows a typical oxygen sensor for closed-loop control. The remaining hardware, such as the electronic fuel injection system or improved carburetor, control system and three-component catalytic converters, appear to be demonstrable by 1976 and mass-producible by 1980. However, the system requires, as in any catalytic system, lead- and phosphorus-free fuel to prevent poisoning of the catalyst.

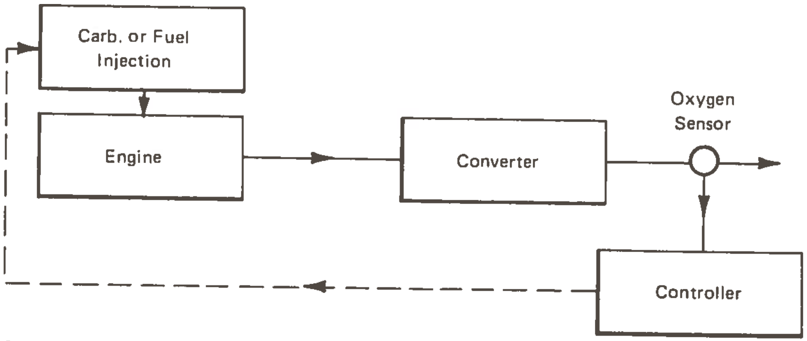
If an engine is not properly maintained, the catalyst may get hot enough to be damaged. Misfiring spark plugs would permit an excessive volume of unburned hydrocarbons to reach the converter. Combustion within the converter could cause serious overheating. Faulty distributor caps and high-tension cables can also cause misfiring. A clogged air cleaner, dirty carburetor or sticking choke could also produce the rich mixtures that could destroy the converter. The auto manufacturers are incorporating over-temperature safety devices to protect the catalyst (see Table 4-13).

Indications of how difficult these two problems are to overcome may be judged from EPA hearing reports on the difficulty Ford, Chrysler, and General Motors are having in passing EPA durability tests using open-loop control system and catalytic converters for emission control for 1975. The real test will come when the 1975 vehicles, which will have catalytic converters, are operated by the public.

The closed-loop control system may help to overcome the problem of proper engine tune, and it is only for this reason we have considered this system. We do not believe an open-loop system will be capable of meeting durability test standards as a long-term solution. Cost estimates of the total system are not valid at this time, but in our judgment the initial cost difference should range from $250 to $500.00 for those pieces of hardware that would replace conventional carburetors and ignition systems and added feedback controls and catalysts.

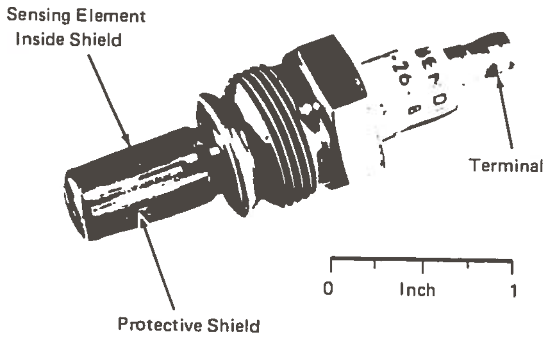
The possible repair and maintenance costs are also difficult to estimate. The FDC certification test procedure specifies that maintenance of the vehicles being certified is limited to major tuneups and certain prescribed replacement parts, such as spark plugs, breaker points, condensers, and the like. We have assumed that the first owner will not have to average more than an additional $10.00 to $30.00 per year in cost for repairs and maintenance, mostly for oxygen sensors.

While this approach appears technically feasible, it remains to be seen whether catalytic systems will prove durable enough for continual effort in their development. On the basis that they do prove durable and that an oxygen sensor can be developed with the life approximately the same as the spark plug, that is 10- to 15,000 miles before replacement, then we see this as an interim approach for the 1974-1980 time span until other engine concepts can be developed and mass-produced.



Source: Pond, J.B., "Controlling Emissions," *Automotive Industries*, November 1, 1973.

FIGURE 4–16 SCHEMATIC OF STOICHIOMETRIC AIR/FUEL RATIO ENGINES USING CLOSED-LOOP SELF TUNING SYSTEMS AND CATALYTIC CONVERTERS



Source: Reddy, J.N., "Closed Loop Emission Control for Automotive Engines," *Bendix Technical Journal*, Spring, 1973.

FIGURE 4–17 OXYGEN SENSOR FOR CLOSED-LOOP CONTROL

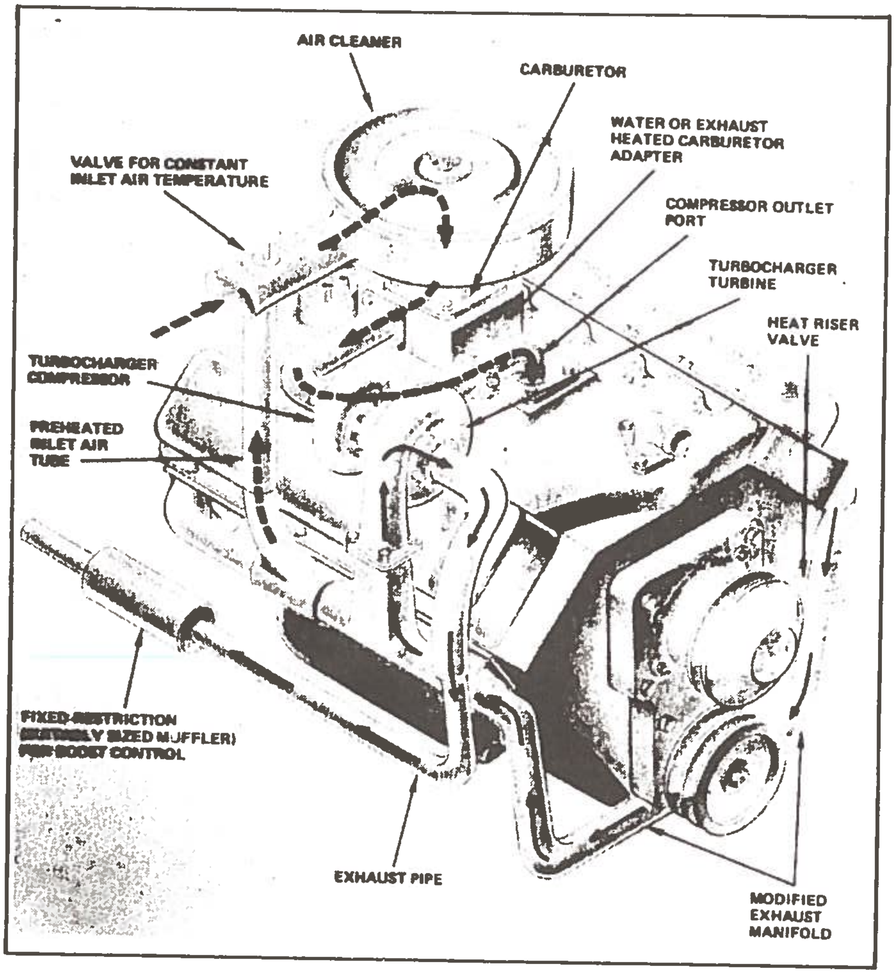
A lot will depend on the experience gained with the oxidation catalyst coming on the market in the 1975 model year cars. Another important factor is the future success of the improved 1976 carburetor which may be capable of operating at stoichiometric conditions without feedback control.

4.3.3.4 Turbocharged Spark Ignition Engine

The specific fuel consumption (BSFC) of a gasoline engine reaches undesirably high values (>1.0 lb. fuel/BHP-hr) at light loads (e.g., <10% of full load). When a large engine is installed in an automobile (e.g., 250- to 300-hp in a 4000-lb. car) to provide good acceleration performance, the engine power requirement during low speed cruise of, say, 30 to 40 mph is far below that required for peak power and its BSFC may reach 1 lb. fuel/BHP-hr, or greater, thus giving rise to poor cruise fuel economy. An alternative would be to install a smaller displacement engine that had one-half or two-thirds of the full load power capability in the naturally aspirated mode and to employ turbosupercharging to reach the same general level of peak power, while still retaining good acceleration performance. With this system the cruise power level would be more favorable for yielding an acceptable specific fuel consumption. Figure 4-18 shows a typical turbocharger installation.

The implementation of this idea would require an exhaust gas turbine which would extract energy from the exhaust of the internal combustion engine. The turbine, in turn, would drive an air compressor. The compressed air would then be fed to the engine's air inlet in place of the usual natural aspiration of ambient air. With this system, when the driver required performance for passing another car or accelerating, the turbocharger would, in effect, give the smaller displacement engine output power equal to that of the larger naturally aspirated engine. During cruise conditions, the turbocharger would be inactive and the smaller engine would operate more nearly as a naturally aspirated engine; however, the throttle setting would be further opened, and the engine would be more fully loaded and operating more efficiently.

When turbocharging is used to increase the power output of the smaller engine, either one of two actions is generally taken; either the octane rating of the fuel must be increased or the compression ratio of the smaller engine decreased to prevent detonation in the combustion chamber; water injection, and intercoolers have been used for this purpose as well. There is also a possibility of reducing detonation (mechanical octane number) by combustion chamber design and this presumably would be explored during a complete engine/turbocharger development program. For purposes of comparing the smaller turbocharged engine with the naturally aspirated larger engine of about equal power output, let us assume that the octane rating of the fuel will remain constant at 91. Therefore, the compression ratio of the smaller turbocharged engine would have to be reduced to the level necessary to prevent detonation. The advocates of turbocharged engines claim that the net mechanical efficiency is higher, because the friction losses and the pumping losses are lower. However, since the smaller engine has a lower compression ratio, the expansion of the combustion products which perform the work is less and therefore the thermal efficiency is less.



Artist's Sketch of a Typical Turbocharger Installation on a V-8 Engine

Source: Nelson, H.M., "Turbochargers: Are They on the Way?" *Automotive Industries*, March 1, 1973, Page 30.

FIGURE 4–18 TYPICAL TURBOCHARGER INSTALLATION ON A V-8 ENGINE

The problem in designing this system is to match the characteristics of the turbine, the compressor that is driven by the turbine, and the characteristics of the smaller engine, particularly its compression ratio, such that the gain in mechanical efficiency is greater than the loss in thermal efficiency due to reduced compression ratio. During the course of this study, we talked with a company which has been actively working on this problem of matching turbocharged to small displacement engine. This company, the Airesearch Industrial Division of the Garrett Corporation, of Los Angeles, California, started from a background of designing, developing, and producing turbochargers for medium horsepower diesel engines. In 1958 and 1959, Garrett started to apply its experience in developing passenger car turbocharged concepts.

Garrett's work has resulted in a number of successful installations which have proven the feasibility of its approach. The company feels that by increasing the horsepower of an engine using a turbocharger degradation of the longevity of the engine is not a problem, providing detonation is not present. In most present car applications the total available horsepower from an engine is rarely used, and the longevity of the engine, as they are designed today, is limited far more by the inertial effect of a high-speed engine than by the increased pressure loading caused by turbocharging. In fact, Garrett feels that the added pressure effect caused by the turbocharging could actually offset some of the inertia effect, particularly in the connecting rod bearings.

The engine itself does not appear to be the problem. However, the drive train components have been known to experience shorter operating lives if not properly matched to the torque output of the engine. Another factor to consider is spark plug life; however, development work has indicated that by proper matching of heat ranges the spark plug life can be comparable to present day operations.

The work to date has not been focused on measuring fuel economy improvements on the basis that performance would be identical. Usually it has been the goal of the developer to reduce pollution or to improve the output of a given engine. Recently, however, the Airesearch Company has set up a comprehensive test program to determine what the fuel economy improvement would be, if any, when a naturally aspirated engine is matched to a turbo-charged smaller engine yielding the same performance and operating with the same octane number fuel. Comprehensive results are not yet available from this test program. We suggest the reader refer to Appendix III, Section I, pages 86-92, but he should be cautioned that this information is preliminary data and not necessarily complete.

To further substantiate the possible merit of this approach we examined the work done by Mr. Earl Bartholomew[34] of the Ethyl Corporation who concluded that if a means could be developed to allow the smaller engine to operate in a naturally aspirated mode, except for near full throttle conditions, then an engine having 30% less displacement and supercharged in accordance with the diagram (Figure 4-19) would have fuel consumption per brake horsepower hour at all throttle settings essentially the same as incidated for the larger, naturally aspirated engine. However, in the cruising operation, the fuel economy of the smaller engine would be considerably better than that of the larger naturally aspirated engine, since the smaller engine, also naturally aspirated under these part throttle conditions would require a larger throttle opening and would result in less manifold

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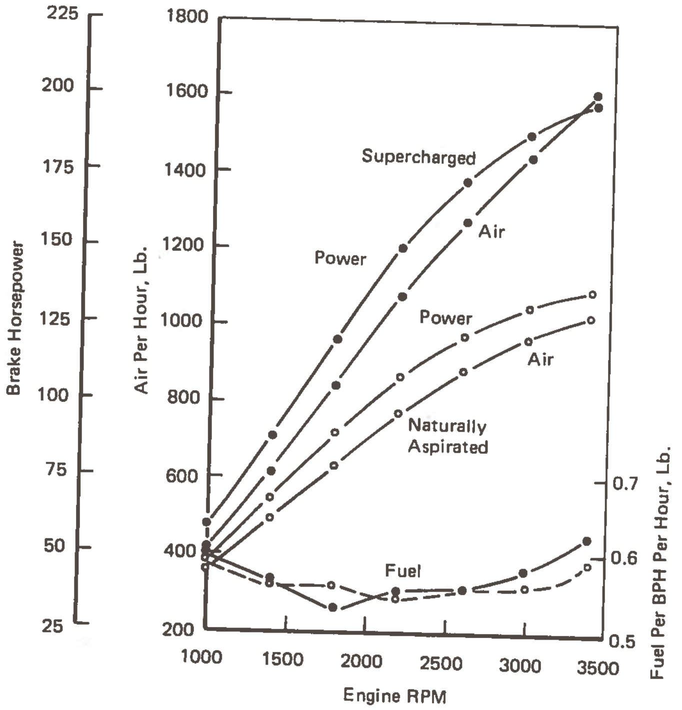
[34] Bartholomew, E., Four Decades of Engine Fuel Technology Forecast Future Advances, presented at SAE National Fuels and Lubricants Meeting, November 2, 1966.



Source: Ref. 29.

FIGURE 4–19 EFFECT OF SUPERCHARGING ON POWER AND CONSUMPTION OF FUEL AND AIR (1940 8-Cylinder Engine) vacuum and smaller pumping losses. Moreover, the mechanical efficiency would be better because of smaller displacement. He also concluded that part of the gain would be offset by the effect of the reduction in the compression ratio that would be required for maintenance for equal knock tendency.

Emission reductions in the smaller turbocharged engine with the same mixture and ignition timing would result because (1) higher engine loads would produce hotter exhaust products and combustion chamber temperatures. However, production of NO_x has to be carefully evaluated and (2) the smaller engine would consume less air and fuel during cruise, idle, and deceleration modes and hence less exhaust products (grams/mile). Exhaust gas recirculation has not been used extensively since NO_x emissions have been quite low without it. EGR systems are mainly used at lower power operation and, if necessary, can feed directly into the intake manifold without affecting the turbocharger.

Johnson and Schweikert of Michigan Technological University pointed out in their paper[35] that, when comparing a turbocharged engine to a larger displacement, of naturally aspirated engine of equal power output, the emissions expressed in grams/mile were relatively unchanged both with and without the use of exhaust gas recirculation. However, turbocharging provided an improvement in fuel economy both with and without EGR. However, they also pointed out that the test procedures used were directed toward proving the feasibility of the concept of reduction in pollution products but they did not carry it to a point of operating the engines under driving conditions. Their tests were performed on dynamometers under steady-state conditions.

The developers of the turbocharged equipment feel that careful matching and development of control systems, one of the major problems inherent with turbocharging systems, can be overcome particularly in the area of response to throttle at low road speeds.

In our opinion, what is required is a complete system design approach involving the redesign of the engine compartment to accommodate the turbocharger with provision made for the higher engine compartment temperature that would be encountered. Another area that has to be studied is the CO generated on cold start because of the induction system of the turbo-charged engine.

Since there is considerable experience in manufacturing turbochargers for diesels, there is reason to believe that the technical problems in applying this concept to a gasoline engine are of a medium to medium-to-low risk. In addition, the requirements for the turbocharger in a gasoline engine are less severe because the boost pressures are considerably lower. This in turn allows modifications to be made in the construction of the turbochargers. The opinions of the industry are that the cost of turbocharging a small engine, including the benefits gained by producing a smaller engine, the possible elimination of exhaust gas recirculation by the reduction of NO_x in the smaller engine and possibly the elimination of a catalytic converter, are worth the effort. Offsetting these gains are possible costs because higher engine output on a continuous basis would require more expensive

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[35] Johnson, J.H., and Schweikert, J.F., A Turbocharged Spark-Ignition Engine with Low Exhaust Emissions and Improved Fuel Economy, SAE 730633, June 18-22, 1973.

exhaust valves for durability. Also, if the carburetor is downstream to the turbocharger, it could be more complex, thus reducing the reliability of the carburetor and increasing its maintenance. Offsetting these disadvantages would be the weight saving resulting from the use of a smaller engine and subsequent lighter chassis components.

For this study we have used our best judgment in evaluating projected costs given to us by a number of sources and are using the range of $150 to $250 for the initial added cost of the turbosupercharged system over a 1973 car.

To complete our evaluation of fuel economy improvement and consequent savings versus cost, we have used the information developed by Johnson and Schweikert,[30] which is presented in Table 4-17. We set the percent of fuel economy improvement estimated to be obtainable in a fully developed production automobile at 5 to 10%.

TABLE 4-17

CALCULATED ROAD LOAD VEHICULAR EMISSIONS AND FUEL CONSUMPTION

		Without EGR				With EGR			
	Bmep (psi)	HC (g/mile)	CO (g/mile)	NO_2 (g/mile)	(mpg)	HC (g/mile)	CO (g/mile)	NO_2 (g/mile)	(mpg)
30 mph road load									
307 turbocharged	29.2	0.06	2.12	0.79	15.9	0.09	1.09	0.54	11.9
450 naturally aspirated	19.9	0.13	2.45	0.84	12.7	0.08	1.41	0.49	9.6
40 mph road load									
307 turbocharged	32.9	0.05	1.82	1.66	15.2	0.07	0.56	0.83	12.2
450 naturally aspirated	22.4	0.04	1.66	1.61	12.6	0.05	0.62	0.69	9.8
50 mph road load									
307 turbocharged	38.7	0.02	0.78	2.74	14.0	0.04	0.54	0.91	11.8
450 naturally aspirated	26.4	0.03	0.90	2.51	12.0	0.03	0.50	0.76	9.5
60 mph road load									
307 turbocharged	46.0	0.02	0.29	4.58	13.2	0.03	0.40	1.54	11.6
450 naturally aspirated	31.4	0.02	0.50	4.21	11.3	0.02	0.44	1.21	9.8

We feel that if, in fact, the above values may be realized under actual driving tests, the approximate timetable for developing and incorporating this concept into production automobiles would be in the 1978 to 1980 period.

In these sections we have discussed spark-ignited, homogeneous air/fuel mixture engines. These engines operate on the principle that the conventional spark ignition causes combustion to occur with propagation of flame at the spark plug which then travels through a somewhat uniform mixture, across the combustion chambers. This approach requires that the air/fuel ratio be rich enough to ignite the mixture and to insure propagation of the flame across the cylinder. Experience has shown that the air/fuel ratio may not vary far from the stoichiometric ratio for proper operation and, therefore, the improvement in thermal efficiency is limited. Furthermore, these engines operate on the principle of throttling the air/fuel mixture to control engine operation, and this increases the pumping losses at low rpm.

4.3.3.5. 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. This would tend to improve the thermal efficiency for a number of reasons:

- A lean air/fuel ratio burns at a lower temperature because of the dilution effect of excess air, and this results in decreased losses because of the ratio of specific heat, $k = c_p/c_v$, which increases for decreasing temperatures.

  The effect is shown in the constant volume air cycle efficiency (Eq. 4-5):

  $$\eta = 1 - \frac{1}{r^{(k-1)}} \tag{4-5}$$

  where

  η = thermal efficiency, and
  r = the compression ratio.

  The heat losses decrease with decreasing temperature, and disassociation decreases as the temperature decreases.

- If the engine system using a stratified air/fuel mixture can be designed to operate without air throttling, or at least minimize the throttling, then the reduced pumping losses and the lower residual charge fraction combine to yield a higher thermal efficiency.

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 over 50 years starting with the early effort of Sir Harry Ricardo[36-42]. The principal aim of all stratified-charge development has been to

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[36] E. Mitchell, et al, A Stratified Charge Multifuel Military Engine – A Progress Report, SAE Paper No. 720051, January 1972.

[37] Norbye, J.P., and Dunn, J., Honda's New CVCC Car Engine Meets '75 Emission Standards NOW, Popular Science, April 1973, pp. 79-81.

[38] Downs, D., The Interrelation of Fuel Quality and Petrol Engine Performance: Present Position and Future Prospects, J. Instit. Petrol., Vol. 49, No. 480, December 1963, pp. 361-370.

[39] Barber, E.M., et al, The Elimination of Combustion Knock, J. Frank. Instit., Vol. 241, No. 4, 1946.

[40] Barber, E.M., et al, Elimination of Combustion Knock – Texaco Combustion Process, SAE Paper No. 473, Summer Meeting, June 1950.

[41] Davis, C.W., et al, Fuel Injection and Positive Ignition – A Basis for Improved Efficiency and Economy, SAE Paper No. 190A, Chicago Summer Meeting, June 1960.

[42] Mitchell, E., et al, Design and Evaluation of a Stratified Charge Multifuel Military Engine, SAE Transactions, Paper No. 680042, Vol. 77, 1968.

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. As we discussed earlier, 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.

Much work has been done on stratified charge engines over the past several years and recently a substantial degree of success has been enjoyed by certain of the developers. Most notable is the work of Texaco† and Ford* who have done much development work for the United States Army Tank and Automotive Command (TACOM).*,† Figure 4-20 illustrates the engine fuel map for the Ford engine without emission control, the lack of which partially accounts for the low B.S.F.C. curves shown.

Both of these major efforts have resulted in the demonstration of stratified charge engines in army trucks. Both improved fuel economy and low exhaust emissions resulted. The Texaco Controlled Combustion System (TCCS) and the Ford Programmed Combustion (PROCO) unit are stratified engines which inject fuel directly into the cylinder and air swirl through an intake valve port. The principal difference is how the air swirl is programmed and the timing of the fuel injection. Both utilized a sparkplug and a relatively sophisticated fuel injection system. A variety of combustion chamber designs have been tried; however, both systems use a design with a cavity or cup in the piston. Figure 4-21 illustrates a typical combustion chamber design for this type of engine. Figure 4-21 shows a typical manner in which the swirl is created by shrouding of the intake valve and by the placement of the nozzle in relationship to the intake port. This diagram is not intended to represent the latest development in this approach. Stratified engines of this type are commonly called undivided or open-chamber engines.

A second type of stratified charge engine has received a great deal of publicity recently. This is known as the Honda-CVVC (compound vortex controlled combustion) engine. This engine differs from the Texaco TCCS and the Ford PROCO engine in that it utilizes a precombustion chamber equipped with a separate carburetor and intake valve to which a rich mixture has been introduced through the intake valve. After combustion starts, it then spreads to the main combustion chamber where the mixture introduced is much leaner having been brought into the combustion chamber through a separate carburetor set for a lean air/fuel ratio. A disadvantage of the CVCC engine is that it is a throttled engine and therefore has larger pumping losses than the TCCS and PROCO engines.

The principal problems with the stratified charge engine to date have 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 a number of 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 for the TCCS engine and perhaps others as well. 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.

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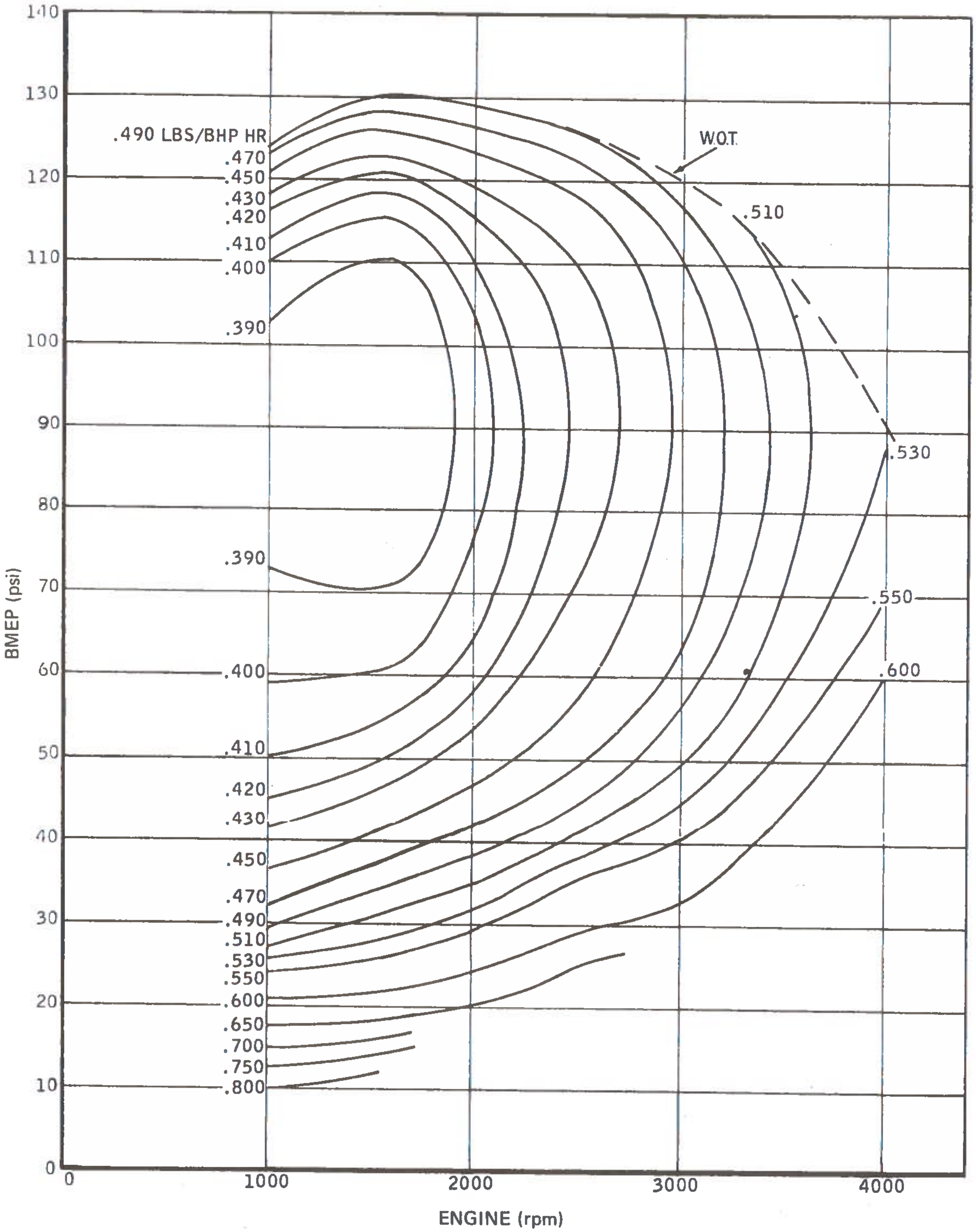
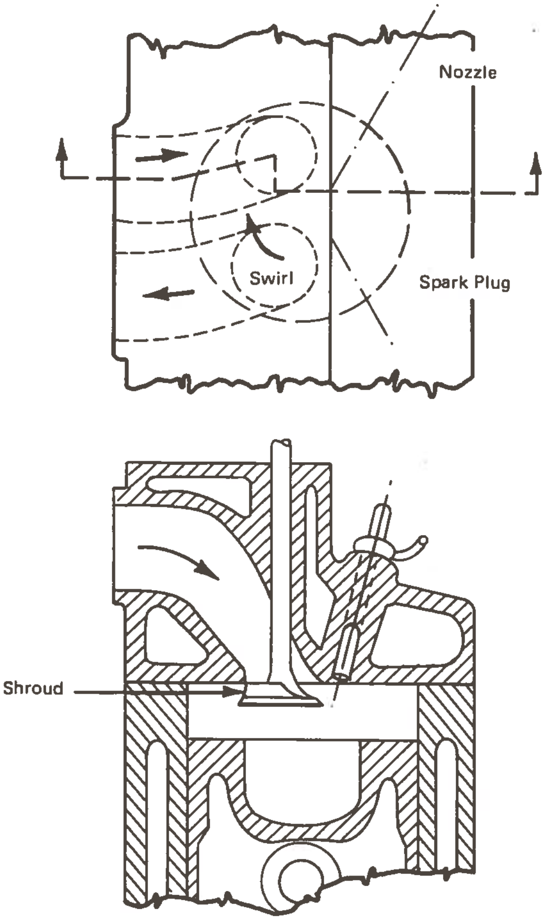
*Ford (TACOM), Contract No. DAAE07-70-C-4374, 1970-1973.

†Texaco (TACOM), Contract No. DAAE07-71-C-0008, 1970-1973.



Source: SAE 680041, 1968

FIGURE 4–20 STRATIFIED CHARGE ENGINE MAP



Source: SAE 680042, 1968.

FIGURE 4–21 STRATIFIED CHARGE COMBUSTION PROCESS – TCCS

Stratified charge engines, particularly the Honda CVVC engine, have shown a good potential for low emissions. EPA reports have indicated that they can meet the interim 1975 emissions standards, albeit, with some loss of fuel economy. The PROCO engine also shows promise of low emissions, although it has not as yet reached the levels of the Honda engine.

Although we were unable to obtain all available up-to-date engine map data in the time frame required for this study from the various developers to perform a complete computer simulation of fuel economy and performance, we did select an engine map[43] to simulate the performance of this type of engine in a standard car. We recognize that the map selected would not be fully representative of the various approaches being developed, or perhaps even show the improvements that have been made since these data were developed. However, we did feel it would show the relative improvement possible with this concept. Table 4-18 illustrates the fuel economy improvement using this engine in the company "X" standard automobile without air conditioning. It must also be pointed out that the acceleration predicted for both cars would be the same. This was accomplished by properly scaling the engine maps so that the 0 to 60 mph and 0 to 30 mph times were identical, resulting in the same 0 to 30 mph and 0 to 60 mph acceleration times.

TABLE 4-18

FUEL ECONOMY COMPARISON FOR STANDARD SIZE CAR WITH NATURALLY ASPIRATED ENGINE AND STRATIFIED CHARGE ENGINE (400 C.I.D.)

		Steady mph Cruise					
	FDC	20	30	40	50	60	70
Company X Reference Car (400 C.I.D.)	11	16.1	19.0	19.8	18.6	16.5	14.6
Stratified Charge (400 C.I.D.)	13.2	21.	24.	23.5	20.2	18.1	14.9

The major cost increment to the initial purchaser would result from the fuel injection system. At the present time, we estimate that the injection system and the ignition system, including the added expense for the complexity of the cylinder head and the intake valve mechanism, would cost

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[43] Bishop, J.N., and Simko, A., A New Concept of Stratified Charge Combustion – The Ford Combustion Process (FCP), SAE Paper No. 680041, 1968.

from $300 to $500. Furthermore, other costs might occur in that there would be an increase in heat rejected to the water jacket due to a larger surface area within the combustion chamber, and this might, in turn, require some enlargement in the cooling system. We have also included the possible added cost for the spark plug modifications required by this approach.

We consider this approach to be a "high risk" concept with good potential for improved fuel economy, and it appears to be worthy of further study and development so that the cost benefits could be compared to other systems. Its attractiveness is based on the fact that current piston engine technology may be utilized and, with the exception of the complexity of the fuel injection systems and spark plug durability, the engine durability should be quite similar. In addition, because it is based largely on using existing parts with slight modifications, it could be commercialized relatively rapidly with only a minor disruption to the industry. Furthermore, if developments proceed with the diesel engine requiring diesel fuel, the TCCS engine, for example, might be the transition engine which would permit the multifuel capability; that is, permit the nation to switch slowly from total gasoline fuel dependency to diesel fuel.

To the best of our knowledge, we have factored in results of emission controls on the stratified charge engine. We feel that the stratified charge engine will meet the 1975 federal emission regulations, will probably meet the interim 1976 federal emission regulations, but will not meet the original 1976 regulations. However, the only way to actually validate the emission of the stratified charge engine is to build and test it against the federal standards.

In addition, we feel that the weight and size of this engine type could be comparable to the present gasoline engine. The problems relating to engine noise or odor require further exploration as we were unable to obtain definitive data on these factors. Furthermore, since we believe that this engine may be developed without the use of a catalyst for emission cleanup, a space, cost, and weight saving would result from the deletion of the catalytic equipment.

The time scale for introducing this engine into production automobiles, in our opinion, would fall in the 1980 to 1984 period. This date is based principally on the time needed to develop a reliable, smooth running engine for production, and the possible need to change over engine lines for the production of this improved engine. Present market value of machines to produce major parts of an automobile engine on an average engine line runs about $30 million.[44]

4.3.3.6. The Light-Weight Diesel Engine

Ricardo Consulting Engineers, Ltd., Sussex, England (combustion engine development engineers with extensive experience in automotive diesel engine development) were 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 widely 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 vehicles with gasoline engines.

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[44] Eschelman, R., Obsolete Engine Lines Cannot be Replaced, Automotive Industries, April 15, 1973.

In these applications all small diesel engines use indirect or divided chamber combustion systems, mostly of the type shown in Figure 4-22. 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, as in Figure 4-23, 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.

Conversion from gasoline to high-speed diesel power is therefore considered to offer significant saving in fuel consumption. It is necessary, therefore, to predict the characteristics of the American specification based on the very well developed European engines.

4.3.3.6.1. State of Development – Engines of this type, mainly of around 130 C.I.D. in four cylinders, have been in production by a number of manufacturers for about 20 years. The requirement has been to match, as far as possible, the gasoline engine it replaces and to combine this performance with the dual diesel attributes of thermal efficiency and durability.

Improvements in mechanical design, along with developments in both the combustion process and fuel injection equipment over this period, have resulted in high-performance engines with durability in excess of 100,000 miles between major overhauls and at an initial cost which is recovered during the first 25,000 miles of operation.

4.3.3.6.2. Present Problems – The three major problems of the diesel engine are noise, smoke and smell, all of which are under continuous study by diesel researchers. However, all can be minimized particularly in the case of the indirect injection engines.

Other problems of the small European automobile diesel engine are cold starting, vibration, increased weight and cost. All these problems are covered in later sections.

4.3.3.6.3. Potential Fuel Usage and Performance Evaluation

4.3.3.6.3.1. Fuel Economy and Emission Results – 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. This is shown in Figure 4-24 which compares the steady-state specific fuel consumptions of a European diesel engine and the gasoline engine of the same output which it replaces. 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. The results of these characteristics are fuel saving under various duties in European vehicles as follows:

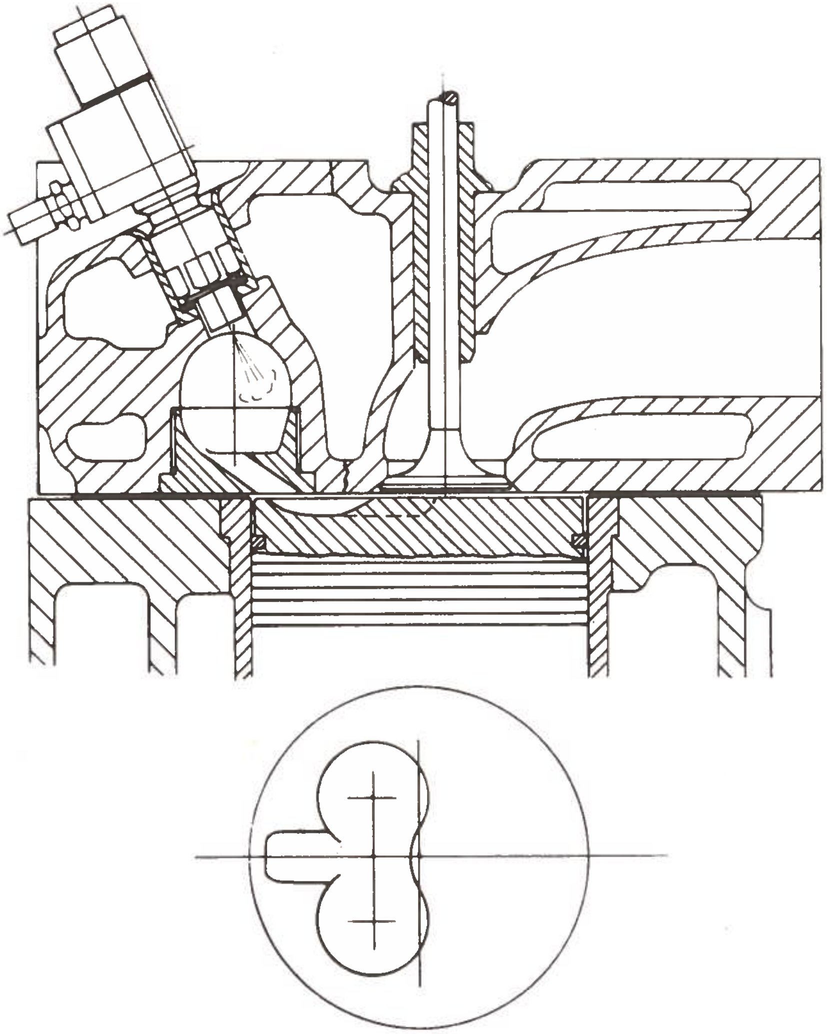


FIGURE 4–22 RICARDO COMET Vb INDIRECT INJECTION COMBUSTION SYSTEM PROPOSED FOR LIGHT-DUTY PASSENGER CARS

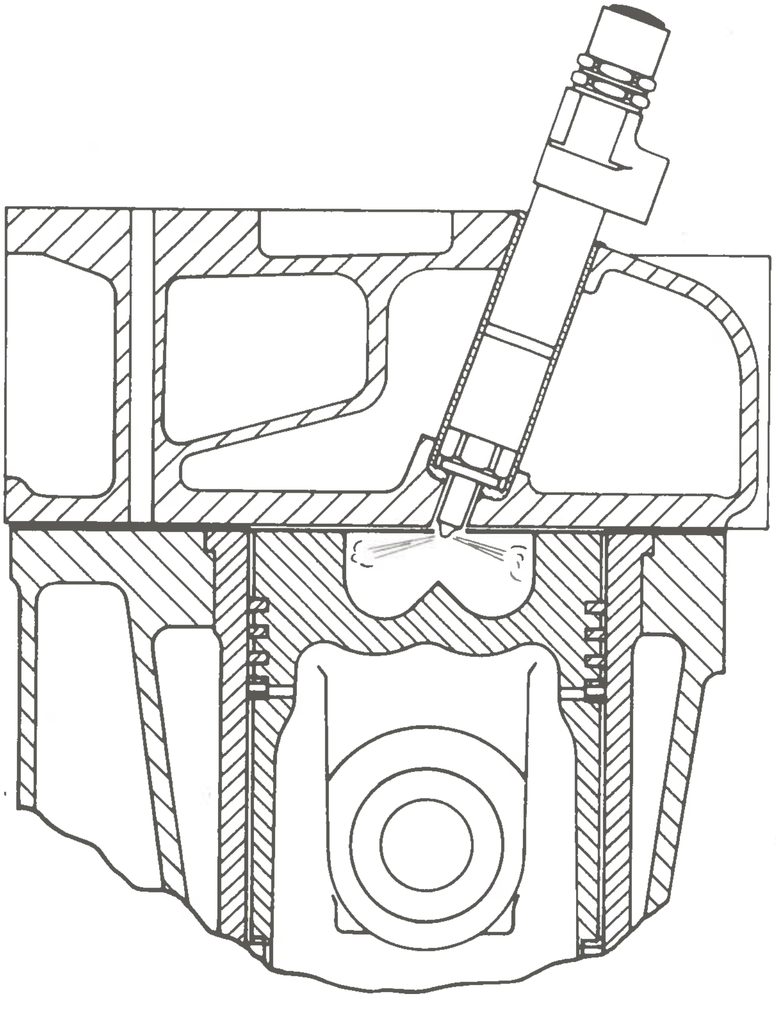


FIGURE 4–23 TOROIDAL BOWL DIRECT INJECTION COMBUSTION SYSTEM AS COMMONLY USED IN TRUCK DIESELS

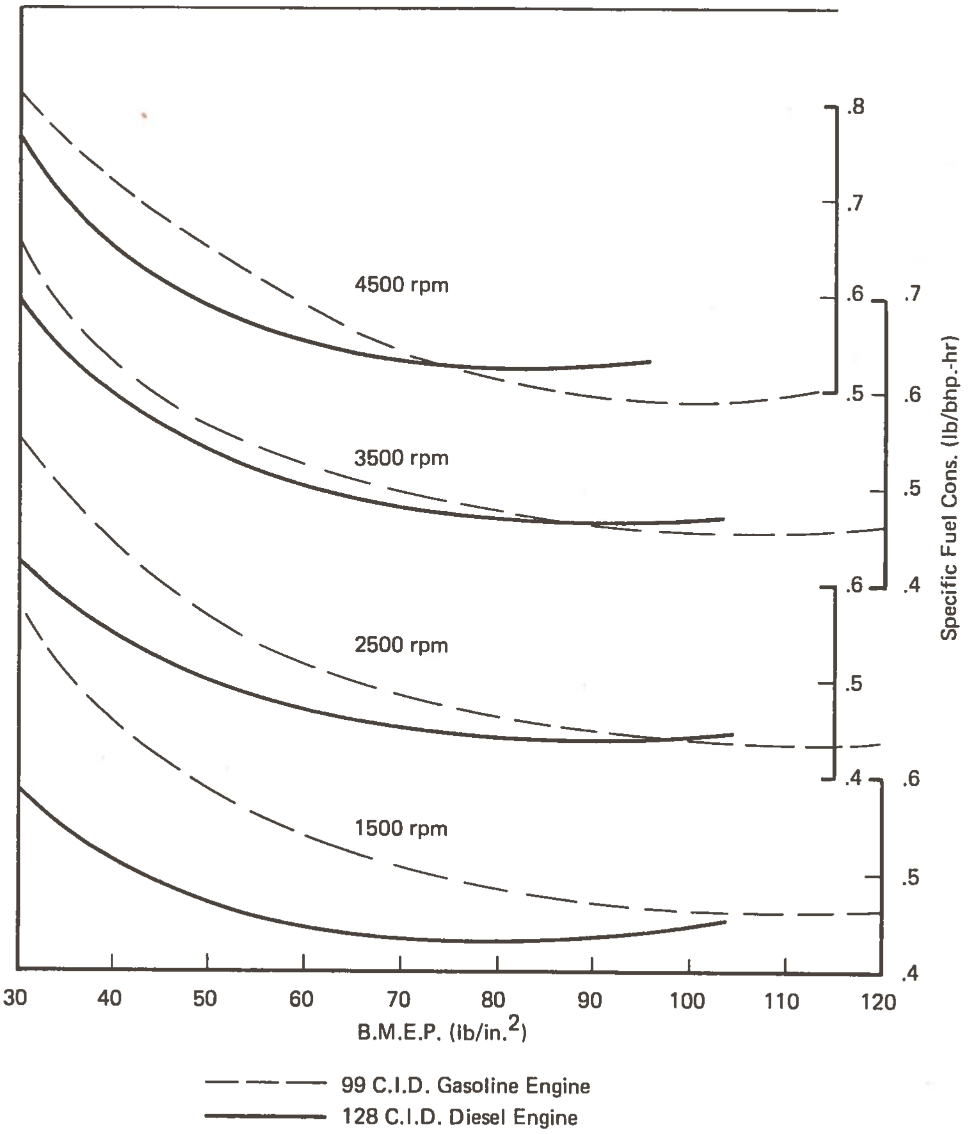


FIGURE 4–24 **COMPARISON OF SPECIFIC FUEL CONSUMPTIONS FROM ALTERNATIVE GASOLINE AND DIESEL AUTOMOBILE ENGINES**

Driving Duty	% Saving
Highway	5%
Suburban	30%
Urban	50%

It is a requirement of this study that the vehicle performance may not be sacrificed in the interest of economy and, therefore, the diesel engine must match the performance of the gasoline engine it replaces. This is not, however, a serious problem because the engines currently in use in the compact and standard cars selected have ratings around 0.4 to 0.5 hp/in.^{3} displacement. The high-speed, light-weight diesel engine can achieve this performance level in naturally aspirated form and at the same piston speeds and with a satisfactory torque backup.

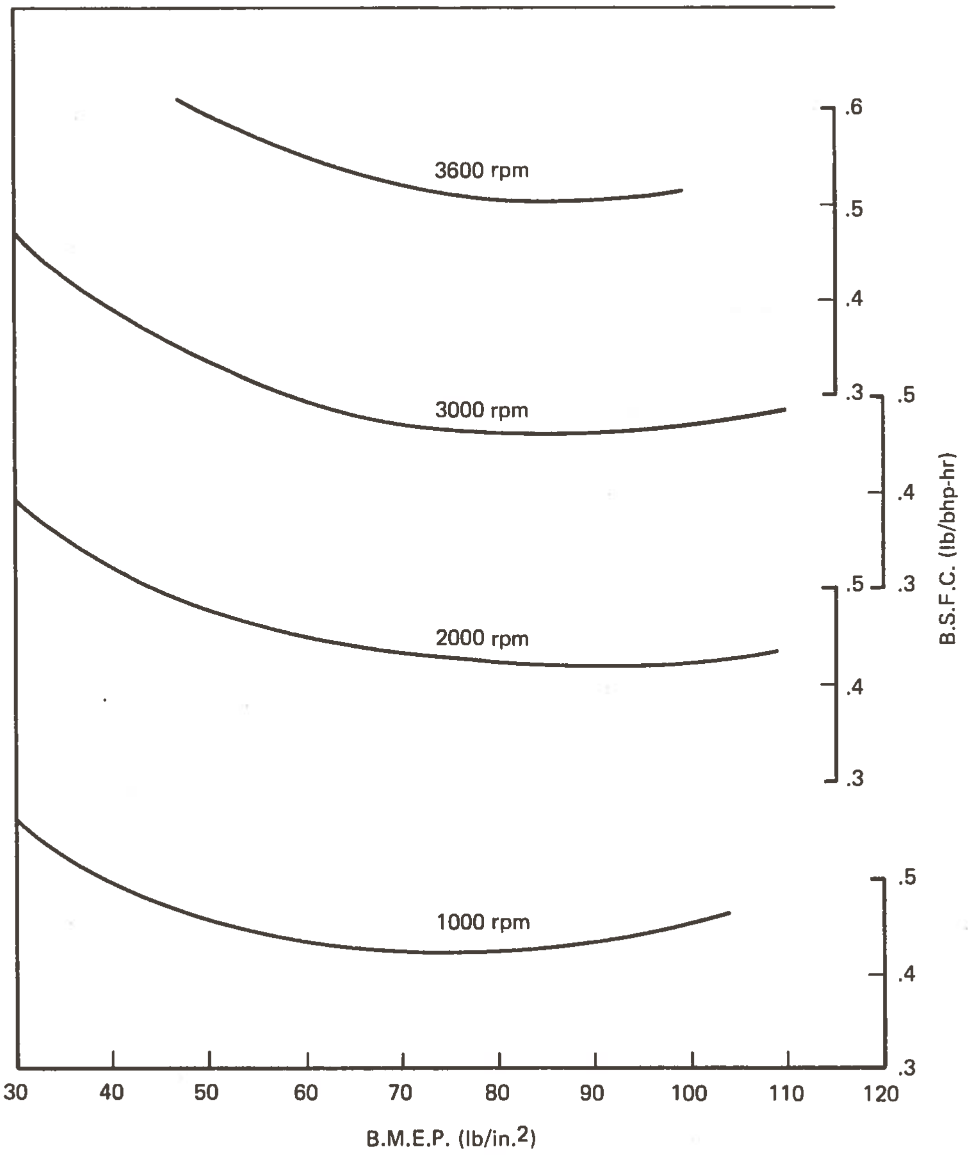
For the power levels required of 100 and 150 hp from in-line 6-cylinder and V-8 engines respectively, the cylinder sizes and piston speeds are very close to those currently in use in European diesel engines. Consequently, the specific fuel consumptions of the proposed engines are also very similar and are shown in Figures 4-25 and 4-26. The main factor which will determine the actual vehicle fuel consumption will be the vehicle weight and road load and, therefore, the load factor at which the engine will operate for most of its time.

Computer simulation of fuel economy for the diesel engine when directly substituted into the reference vehicles resulted in the data presented in Table 4-19. The results of Table 4-19 were determined on the basis that the substitution of a proper size diesel engine would yield comparable performance (acceleration).

TABLE 4-19

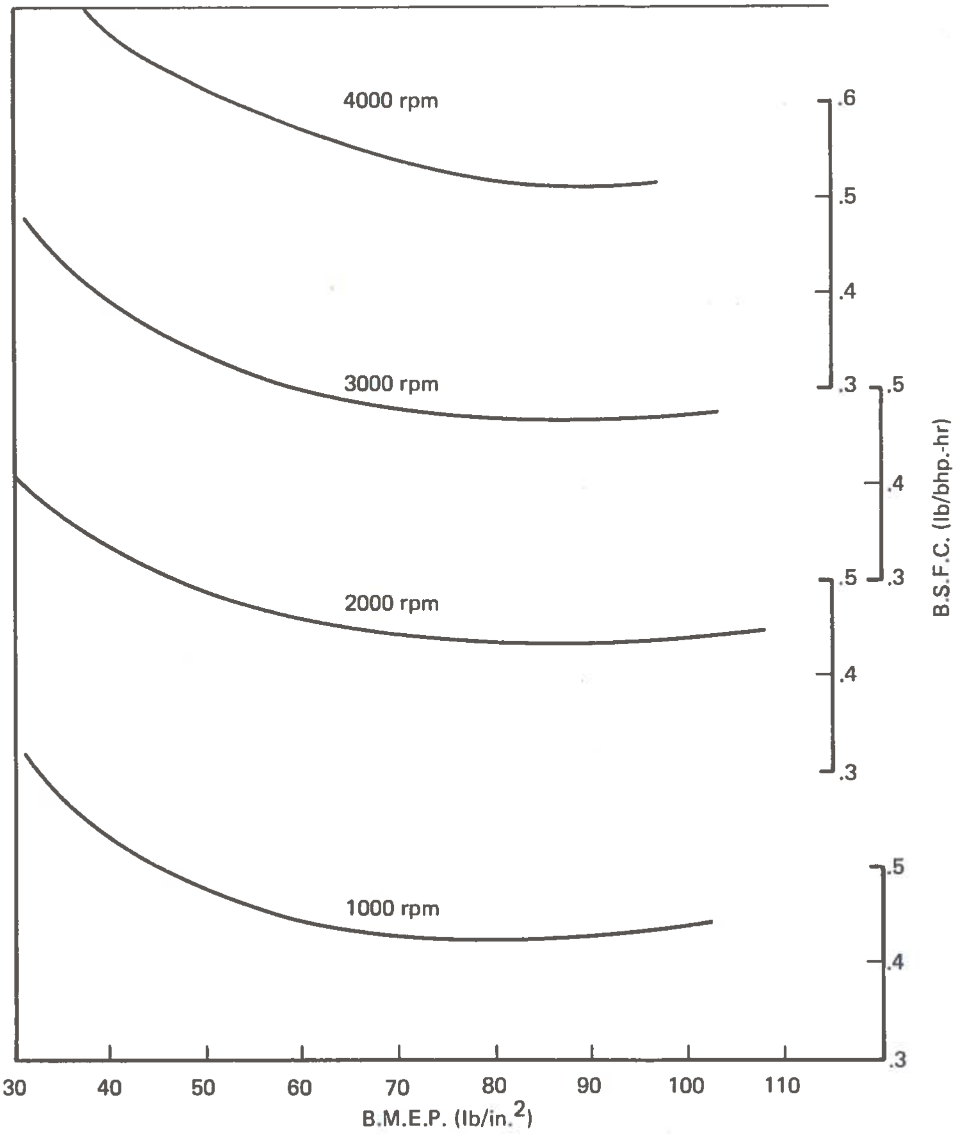
FUEL ECONOMY COMPARISON FOR GASOLINE VS DIESEL CARS OF EQUAL SIZE AND PERFORMANCE

			Fuel Economy at Steady Speed (mpg)					
Size Car	Company	Fuel Type	F.D.C.	30	40	50	60	70 mph
Std.	X	Gas	11.0	19.0	19.8	18.6	16.5	14.6
Std.	X	Diesel	13.5	21.0	20.8	18.8	16.0	–
Std.	Y	Gas	10.4	18.6	18.5	17.3	15.4	14.0
Std.	Y	Diesel	13.8	22.2	21.6	19.8	17.1	14.8
Compact	X	Gas	17.4	27.9	27.1	23.8	20.7	17.8
Compact	X	Diesel	21.4	30.5	27.7	24.6	21.3	18.4
Compact	Y	Gas	13.8	21.7	20.4	19.4	16.9	13.5
Compact	Y	Diesel	19.7	30.5	27.4	24.0	20.6	17.5



Bore Dia.:	3.5 in.	Ricardo Comet Vb Chamber
Stroke:	4.1 in.	Comp. Ratio: 20.5:1
C.I.D.:	237	Rated Speed: 3600 rpm

FIGURE 4–25 **ESTIMATED PERFORMANCE OF 100-HP, 6-CYL., IN-LINE DIESEL ENGINE FOR COMPACT CAR – LOAD RANGE CURVES**



Bore Dia.:	3.8 in.	Ricardo Comet Vb Chamber	
Stroke:	3.55 in.	Comp. Ratio:	20.5:1
C.I.D.:	326	Rated Speed:	4000 rpm

FIGURE 4–26 ESTIMATED PERFORMANCE OF 150-HP V-8 DIESEL ENGINE FOR STANDARD CAR – LOAD RANGE CURVES

4.3.3.6.3.2 Emissions – In addition to the gaseous emissions[45] of NO, CO, and unburned hydrocarbons, the diesel engine emits smoke comprising carbon particles at low air/fuel ratios that are responsible also for characteristic diesel odor. All well developed diesel engines produce very low levels of both CO and unburned hydrocarbons (compared with the gasoline engine) on account of the lean air/fuel ratios used. European vehicles having power/weight ratios somewhat less than American automobiles fall comfortably within the levels of this study of CO (3.4 g/mile), HC, (0.41 g/mile) and NO_x (2.0 g/mile), respectively, without recourse to exhaust gas treatment.

Oxides of nitrogen from the European car also fall well within the 2.0 g/mile limit without deviation from normal running conditions set for performance and noise. Typical gaseous emissions from a European car weighing 3000 lb and having a 60-hp diesel engine on the light-duty diesel CVS cycle are:

HC: 0.2 g/mile
NO_x: 1.2 g/mile
CO: 1.6 g/mile

In the absence of any similar results from either engines or vehicles approaching in size and weight those of the American automobile, predictions based on the effects of varying both the power/weight ratio and road load on European results have to be made.

The effect of an increased power/weight ratio is to increase all three gaseous emissions, since the increase in mass flow outweighs the drop in concentrations, particularly of CO and NO_x with load factor.

From the limited information available at the present time, we predict that the American engines in question, in normal performance (not low emission) trim, will return emission levels as tabulated below:[46],[47]

			g/mile		
Vehicle	**Weight (lb)**	**Power (hp)**	**HC**	**CO**	**NO_x**
Compact	3200	100	0.2-0.3	<3.0	1.5-1.7
Standard	4200	150	0.35-0.45	<3.5	2.0-2.5

Significant reduction in NO_x can be achieved by the retard of injection timing, but with some sacrifice of fuel economy. For example, the standard automobile could be brought well within the 2

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[45] Millington, B.W., and Hartles, E.R., Frictional Losses in Diesel Engines, SAE Paper No. 680590.

[46] Walder, C.J., Reduction of Emissions from Diesel Engines, SAE Paper No. 730214, January 1973.

[47] Downs, D., "The Diesel Engine As a Low Emission Power Unit for Automobiles," presented at first Symposium on Low Pollution Power Systems Development, October 14-19, 1973.

g/mile limit with a loss of fuel economy of some 2-3%. Alternatively all the emissions levels could be reduced if the standard automobile were fitted with a 130-hp engine, giving the same power/weight ratio as the compact car.

In normal performance black smoke is not a serious problem for the small diesel engine. The level over the full-load torque curves ranges from 2-6% opacity, and only exceeds the 5% level at the lowest speed of 1,000-1,200 rev/min which represents a very small proportion of the operating time. These low levels are a characteristic of the indirect injection combustion system which maintains a low smoke level up to a high load factor. Figures 4-27 and 4-28 illustrate the smoke characteristics over the full-load torque curves.

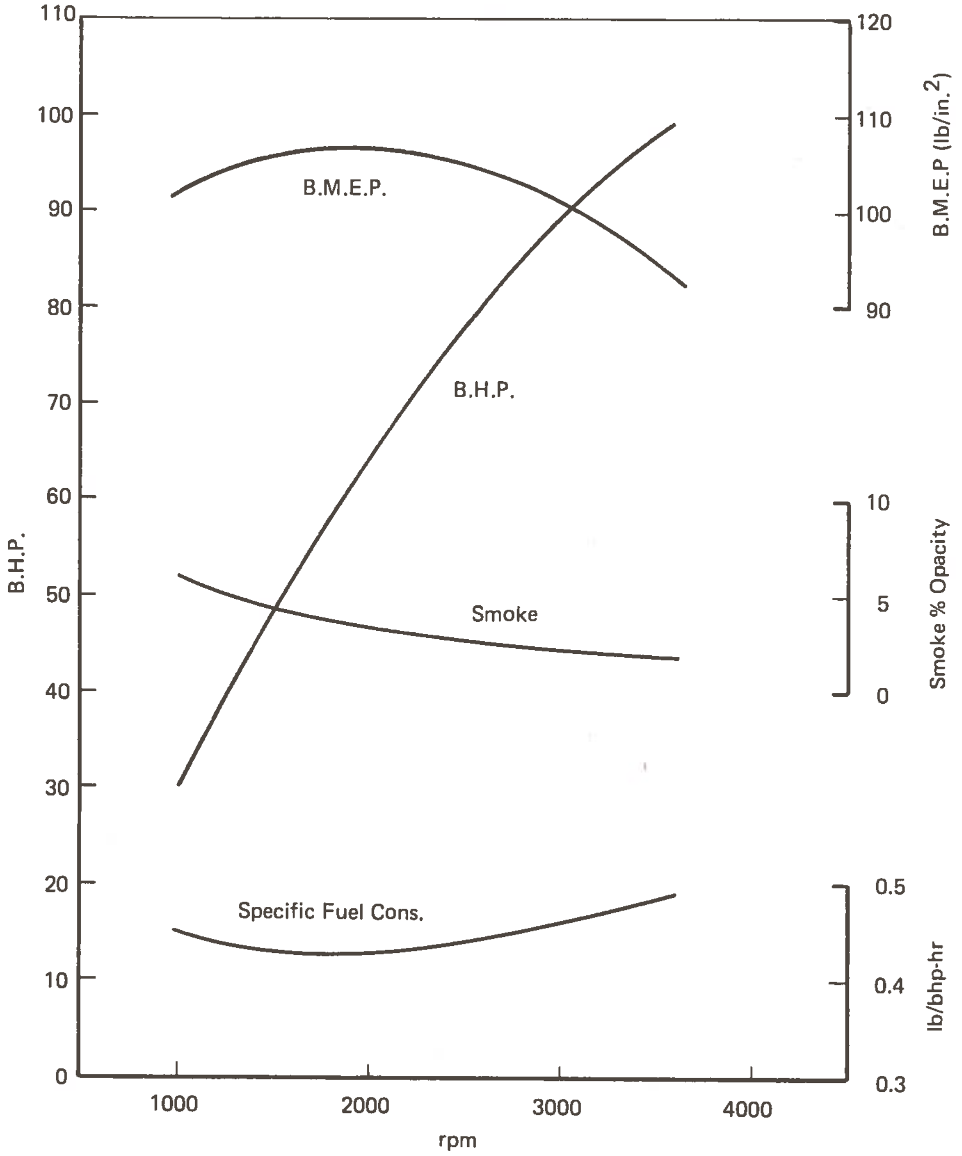
Odor is a subject which is difficult to treat objectively at this stage, since there is no universally accepted method of measurement. There is little doubt that there is a problem particularly associated with the truck and bus size diesel engine which is largely responsible for the "smelly diesel" impression held by the "man in the street". This problem is minimized in the indirect injection system both at high load, when the odor is associated with the smoke level, and at light-load, cool-engine conditions. In the Ricardo Comet combustion system, the lower part of the swirl chamber (see Figure 4-22) is heat-insulated to ensure rapid warmup of the wall where fuel may be deposited, thus ensuring more complete combustion and reduced odor during startup and under light-load operation.

4.3.3.6.3.3. Chance of Success – The diesel engine as an alternative power plant to the gasoline engine for automobiles has been established in Europe for some 20 years. Its success in achieving significant reductions in fuel consumption is beyond doubt. Its potential for achieving similar results in the American automobile is also promising, although the precise degree of improvement can only be predicted at this stage.

Present design technology can ensure a high level of performance and durability with prototype development limited to one or two discrete areas, such as matching fuel injection characteristics for best performance, emissions, etc. The chance of success is therefore high.

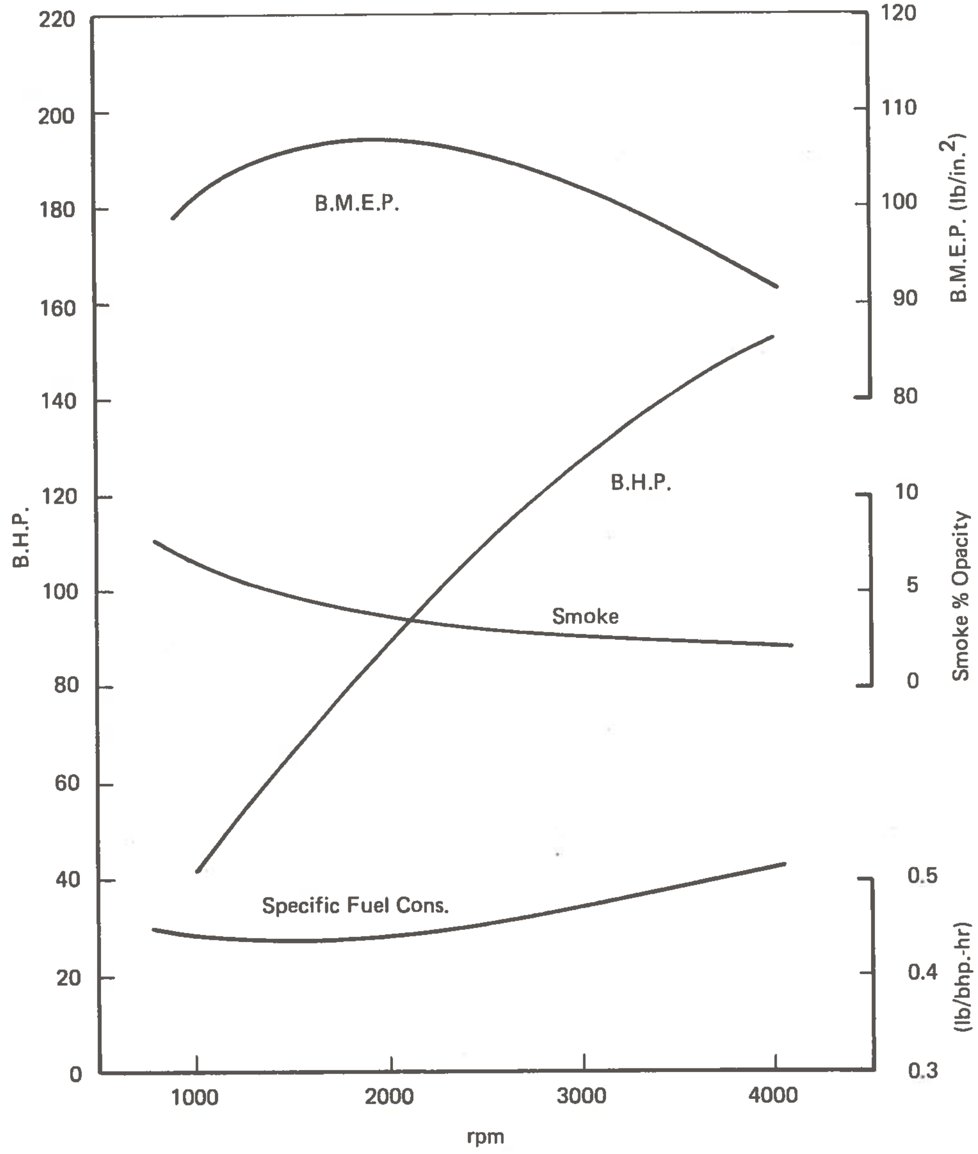
4.3.3.6.3.4. Complexity – To a first approximation the complexity of the diesel is similar to that of the gasoline engine, the main differences being in the shape of the combustion chamber and the replacement of the carburetor and ignition system by the fuel injection equipment and starting aid. However, in these areas the diesel engine is somewhat more complex than the normal gasoline engine.

The combustion system, as shown in Figure 4-22, has the compression volume at T.D.C. divided into two parts, a quasi-spherical swirl chamber in the cylinder head being connected to the space over the piston by a throat which is tangential to the head chamber. Fuel is injected via a variable orifice injector and ignited in the head chamber in which the air charge, having entered through the throat, is rotating at high speed to achieve a high rate of fuel air mixing. Further mixing occurs during expansion, when a rich mixture enters the piston cavities generating further air swirl.



Bore Dia.:	3.5 in.	Ricardo Comet Vb Chamber	
Stroke:	4.1 in.	Comp. Ratio:	20.5:1
C.I.D.:	237	Rated Speed:	3600 rpm

FIGURE 4–27 ESTIMATED PERFORMANCE OF 100-HP, 6-CYL. IN-LINE DIESEL ENGINE FOR COMPACT CAR – TORQUE CURVE



Bore Dia.:	3.8 in.	Ricardo Comet Vb Chamber	
Stroke:	3.55 in.	Comp. Ratio:	20.5:1
C.I.D.:	326	Rated Speed:	4000 rpm

FIGURE 4–28 ESTIMATED PERFORMANCE OF 150-HP V-8 DIESEL ENGINE FOR STANDARD CAR – TORQUE CURVE

The modern distributor type of fuel injection pump, though moderately complex, has relatively few parts, some of which, however, are of high-precision manufacture. Nevertheless, the parts are simple in design and lend themselves to high-volume automated production. This applies also to the fuel injectors which, though complex compared with the spark plug, may have a life approaching that of the engine with negligible maintenance. The complexity of the diesel engine does not exceed that of the gasoline engine, and comprises known technology, and would not require E.G.R. valves, air pumps, reactors, etc.

4.3.3.6.4. Cost and Time Considerations

4.3.3.6.4.1. Initial Cost Estimate – The manufacturing cost differential between the gasoline and diesel engine is extremely difficult to establish. This is, in part, because manufacturers who make both gasoline and diesel vehicles seldom have the necessary breakdown of costs available. The selling price of diesel vehicles is no guide to the manufacturing cost, being more an indication of what the market will stand or a means of controlling the extent of the market. Another factor is undoubtedly the relative production quantities. This consideration not only affects the cost of the engine itself, but also that of the fuel injection equipment which forms a major item in the increased cost and is very much dependent on the volume produced.

Such data as have been obtained indicate that in Europe the diesel engine costs about 50% more to produce than the gasoline engine. About half of this increase is attributable to the cost of the fuel injection equipment. The remainder is attributed to the greater complexity of the engine design in the region of the combustion chamber, superior materials, larger starter motor, and the like.

Apart from the actual increased number of fuel injectors corresponding to the number of cylinders, the remainder of the equipment peculiar to the diesel engine would not increase *pro rata* with the engine size, assuming similar production quantities. The increased cost of the 6- or 8-cylinder American diesel engine may therefore be 25-30% more than that of the gasoline engine.

For this study we have used an initial cost increase for the diesel engine and necessary vehicle modifications of $500-$700.00 for both compact and standard-size cars.

4.3.3.6.4.2. Availability within Time Frame of Demonstration – There are no diesel engines in production at the present time which will satisfy the specifications required for demonstration in place of the gasoline engines of the compact and standard American automobiles. It will therefore be necessary to design, manufacture, and develop prototypes for this purpose. Starting with a clean sheet of paper, but with a background of experience from the design of many European diesel engines of similar cylinder size and specific performance, we figure the time scale for the two engines to reach a demonstrable form would be as follows:

	Months
● Time for design and manufacture to point of first engine running	18
● Development, including injection matching	6
● Limited amount of proof testing	4
	28

The above figures represent the times normally involved and would result in the two engines progressing simultaneously, being ready for demonstration in late 1976 if contracts were placed in mid-1974. However, currently the prototype manufacturing facilities throughout the industry are heavily loaded and the above total times could be extended to 34 months. Some saving in design and procurement times could be made if the engine specifications were modified to gain some commonality of parts such as pistons, bearings, valves, and perhaps even cylinder heads.

4.3.3.6.4.3. Time to Implement to Mass Production – Assuming that the production engines are broadly based on the prototypes above, we opine the time required to reach commencement of mass production will be controlled by the design and procurement of the tooling. Recent European experience suggests that this would take another two years during which time any modifications and further tests of the engines to meet the requirements of the selected manufacturers could be undertaken.

It is therefore apparent that while the target demonstration date cannot be met by designing and procuring new prototype engines, production could commence before 1980.

4.3.3.6.5. Size and Weight

4.3.3.6.5.1. Envelope Size – The two diesel engines are very similar in cylinder size and have the same configurations as the gasoline engines they will replace. The dimensions in which they will differ are the cylinder block height above the crankshaft center and the length of the cylinder block.

In the interest of ensuring satisfactory conditions for the top piston ring, the diesel engine top ring-land is made deeper than the gasoline. This has the double effect of locating the ring at a cooler level in the piston; thus at the top of its stroke it will be operating on a cooled part of the cylinder bore in spite of the thicker top deck of the cylinder block. This will result in the block height being up to 0.75 inch taller than the gasoline engine.

It is also found necessary to increase the center distance between bore centers from 1.17 to 1.25 times the bore diameter to ensure adequate metal and coolant passage between the cylinders. This results in the V-8 diesel engine being 0.9 inch longer than the gasoline engine. The length of the inline 6-cylinder engine would not be affected to the same degree.

The envelope size is, of course, also influenced by the auxiliaries, pipe work, etc., and will depend on the design technique as well as pure technical requirements. In these circumstances the increases estimated above may not be significant. The increase in envelope size at worst could be as follows:

Dimension (in.)	Compact	Standard
Length	0.5	0.9
Width	0	1.0
Height	0.75	0.5

4.3.3.6.5.2. Weight – With a general increase in dimensions of the bare engine of approximately 5%, the weight would increase by 15% compared with the gasoline engine. The auxiliaries on the gasoline engine amount to about 20% of the total engine weight and could be increased by a further 10 pounds each from the fuel injection pump, starter motor, and flywheel. The breakdown of engine weights should be as follows:

	Weight (lb)			
	Compact		Standard	
	100-hp, inline, 6-cylinder		150-hp, V-8	
Engine	Gasoline	Diesel	Gasoline	Diesel
Bare engine	330	380	375	430
Auxiliaries	100	130	100	130
Added weight for supporting structures	0	60	0	60
Total weight	430	570	475	620
% Increase	say 25%		say 25%	

The comparison of engine weights is entirely on the basis of the same materials as the gasoline engine. Substitution of light-weight alloys should be considered.

4.3.3.6.6. Operating Considerations

4.3.3.6.6.1. Durability – The factor which determines the time at which the diesel engine should undergo a major overhaul is cylinder-bore wear. Experience with the operation of several diesel cars has shown this to be dependent, to some extent, on the sulfur content of the fuel and the operating conditions.

When run on fuels having a sulfur content below 0.4%, current European engines approach – and many exceed – 100,000 miles between overhauls, and during this time it may be necessary to inspect fuel injectors once or perhaps twice.

4.3.3.6.6.2. Reliability and Maintenance – The reliability of the diesel engine is one of its major attributes when used in large trucks. This reputation stems from the generally superior materials used in its construction and also the absence of high-voltage ignition equipment. In the small, high-speed diesel engine this reputation is maintained and benefits additionally from the variable orifice injector which does not suffer from hole blocking – and consequent dramatic increases in smoke production – which would cause the vehicle to be withdrawn from service.

Maintenance is confined to the routine changing of lubricating oil and fuel and oil filter elements. Top overhauls involving cleaning away combustion deposits from the combustion chamber and grinding in valves is normally unnecessary between major overhauls. In the event of major engine overhauls, the availability of trained mechanics should not present a problem either for engine or injection repairs.

4.3.3.6.6.3 Noise – The noise level[48] produced by diesel engines can be predicted with considerable confidence from empirical data gathered from noise testing many diesel engines in a sound testing (non-echo) environment. The noise is found to be a function of cylinder bore size, speed, combustion system and fuel ignition quality.

In predicting the vehicle driveby noise, the engine level measured at 3 feet is adjusted in accordance with the inverse square law to 50 feet with account being taken of the shielding effect of the vehicle. In this case the correction is made by subtracting 24.5 dBA from the engine noise level at 3 feet. A further adjustment is made involving the addition of 5 dBA to account for the additional effects of noise sources, such as intake, exhaust, tires, and the like, and deviation from the inverse square law.

The predicted noise levels of the two proposed vehicles under driveby conditions would be:

	Noise Level (dBA)	
Condition	**Compact**	**Standard**
Engine noise at 3 feet	96.5	99.0
Engine noise at 50 feet	72.0	74.5
Correction for other sources, plus deviation from the inverse square law	+5.0	+5.0
Predicted driveby levels	77.0	79.5

These levels are approximately 4 dBA higher than the gasoline engine vehicles, but well within the automobile noise standard of 82 dBA which is the norm in California and New York.

Idling noise has always been a major problem with diesel engine vehicles. The noise observed from the sidewalk is a combination of combustion and mechanical and fuel injection noises of roughly similar levels. The decibel level of this noise is low, but subjectively it is worse than that of the gasoline engine because of its high frequency content. This nuisance can be minimized, however, by careful attention to design details so far as the engine is concerned, and can be further reduced by the adding of noise shielding and absorption in the engine compartments with an increase in vehicle weight of 15-20 pounds.

Internal noise and vibration are very much dependent on the quality of the installation engineering. High-frequency noise from combustion and the fuel injection equipment is not normally transmitted through the engine mounts and finds its way into the passenger compartment through small holes around control cables, wiring, and the like, in the engine bulkhead. Low frequencies stemming from the fundamental firing frequencies or torque reactions are difficult to eliminate in the case of the 4-cylinder European engine. Very low rate mounts result in excessive swing of the engine when starting and stopping, requiring much space around the engine. The increase from 4 to 6 and 8 cylinders largely eliminates this problem by giving a smoother torque pattern from the engine and larger engine mass.

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[48] Scott, W.M., Noise of Small Indirect Injection Diesel Engines, SAE Paper No. 730242, January 1973.

Rubber is normally used extensively in sealing the bulkhead and for engine mounts. Gas and oil fuel causes fairly rapid deterioration of this rubber, and therefore care must be taken in diesel installations to ensure adequate life of these components. Where possible, synthetic rubber should be used or the components protected from the fuel.

In general, we anticipate that internal noise levels can be kept at an acceptably low level in the American automobile.

4.3.3.6.7. Acceptablity to Consumer

In addition to such undesirable features as noise and odor there are some further factors which must be considered. These are discussed below.

4.3.3.6.7.1 Startability – The compression ratio chosen for the small diesel engine is primarily in the interests of cold starting. The upper limit has an adverse effect on friction and therefore performance and fuel consumption. In this cylinder size the use of starting aids is universal either in the form of electrically energized glow plugs in the combustion chamber or some form of intake air heating. The former is the more effective and is most popular in European engines.

With compression ratios of 20.5:1 and a minimum cranking speed of 100 rpm, the use of glow plugs will permit certain starting down to -4°F. Below this temperature other measures must be taken to assure positive starting. At present such methods as electric block heaters, ether sprayed into intake, and dilution of fuel with gasoline are used. We feel that these do not represent a satisfactory solution and identify cold starting (below -4°F) as a major problem requiring further development work to overcome.

The certainty and cleanliness of the start depends very much on the correct use of the starting procedure. The use of a hand switch in many European cars which has to be held for 20-30 seconds to heat up the glow plugs becomes an irksome chore which is often cut short and results in marginal start conditions.

There is scope for the development of automatic start procedures, initiated by opening the car door, or other means, to minimize the actual waiting time. A foot-operated switch is a good alternative, since the glow plugs can be heating, while the driver is fastening safety belts, and the like.

4.3.3.6.7.2 Cold Driveability – Once the engine is running, full "cold engine" power is available with no flat spots under all conditions. This is a feature which is valued by the diesel automobile driver as there is little danger of stalling if power is applied in an emergency.

4.3.3.6.7.3. Hot Driveability – With engine performance matching the gasoline engine, hot driveability will also be matched. However, with the higher power/weight ratios of the American cars, some consideration will have to be given to the engine controls.

European car diesel engines are usually fitted with an "all-speed" governor. This is used for economic reasons since the same unit can be used in automobiles, generator sets, boats, and the like. In the automobile the accelerator pedal is coupled to the speed control lever of the governor and, at all speeds, reduction in fueling follows the governor runout curve. Consequently, the accelerator pedal is at a different part of its travel, depending on engine speed, for the same torque and the pedal travel from zero to full fuel is very small. Consequently, full torque can be applied with very small movements of the pedal and could result in possible shunting with the vehicle in front. The low power/weight ratios of European cars preclude this problem.

The answer is the governor giving idle and overspeed control only with direct torque control by the pedal in between. This sort of system is available on larger truck engines and could be made available for automobile engines also. Transmission requirements are similar to those for the gasoline engine and no special provisions need be made.

4.3.3.6.7.4 Fuel Characteristics – Diesel fuel suffers at low temperatures from the deposition of wax and results in the fuel becoming cloudy if not properly blended at the refinery. The effect is that the wax blocks the fuel filter and the vehicle becomes inoperable. This state of affairs will occur if the vehicle is stored for prolonged periods, i.e., overnight in ambient temperatures 2-5°F below the cloud point of the fuel. To solve this problem, the oil companies adjust the blending of the fuel to assure that the cloud point is unlikely to be reached in the vicinity in which it is sold. A car travelling into a cold area with fuel obtained from a warmer climate would have to have an additive put in the remaining fuel, or properly blended fuel added to the tank. Fuel spillage should be avoided because, being of a higher boiling point, its odor will persist for much longer periods than gasoline.

4.3.3.6.7.5 Cost of Ownership – The two factors to be considered in this respect are initial cost differential and fuel cost and, in the present climate, the latter is a little unpredictable. European experience, on the basis of the fuel saved in general mixed traffic operation and with gasoline and diesel fuel at the same price per gallon, shows the breakeven point to occur between 20- and 30,000 miles.

The cost of maintenance should not increase and could be lower than the gasoline engine. It is therefore likely that the first owner of the vehicle will benefit financially from the change to diesel power provided service arrangements are comparable with present gasoline engines.

4.3.3.6.8. Effect on Other Subsystems – The lower heat rejection of the diesel engine under idling and light load running conditions will mean that the car heater will take longer to become operative following a start from cold. It is estimated that this time could be doubled and it may be necessary to supplement the heater electrically. For this reason – and on account of the greater starting loads – the battery capacity would have to be increased. This would add further weight to the vehicle. However, in general the larger capacity batteries used in diesel cars have a more than *pro rata* life and therefore the larger battery would not add to the operating cost. The increased battery capacity might have to be augmented by the use of a larger alternator. The weights for both of these incremental increases have been included in Section 4.3.3.6.5.2. – Weight.

4.3.4. Transmission and Drive Train Systems

4.3.4.1 Introduction

The modern-day transmission in addition to being automatic in its operation provides two distinct features: (1) a smooth coupling between the engine and rear axle, and (2) a selection of gear ratios. The smooth coupling of the engine and the drive shaft is most notable during the startup of the vehicle. Under startup conditions, the engine is turning at a relatively low rpm rate while the vehicle is completely stationary. As the throttle opening is increased, the power of the engine is automatically applied to the rear end to provide smooth take-off. Without such a feature either the engine would suddenly plunge to an extremely low and intolerable rpm level, or the vehicle would start at extremely high accelerations. The second feature of the transmission is to permit the operation of the engine in a desirable speed range by providing a selection of appropriate gears for the transmission of power to the rear end. The speed range of the vehicle drive shaft for a normal car runs from about 0 to 2000 rpm. The engine, however, can only operate between approximately 800 and 4000 rpm; therefore, several gears must be provided to keep the engine in its 1 to 5 speed range band, while operating over the entire vehicle speed range. These two features – a smooth coupling and selection of gears – are provided in two distinct units of the transmission – the clutch or torque converter and the gear box.

4.3.4.2. Function of Torque Converter versus Gear Box

The torque converter is a device which provides initial torque multiplication, while permitting smooth delivery of engine power to the drive train of the car. The gear box, following the torque converter, provides a selection of gear ratios for coupling the engine power to the rear drive train to achieve good economy and performance. Both the torque converter and the gear box can affect vehicle performance and fuel economy substantially. Therefore it is necessary to consider both the torque converter characteristics and the gear box specifications and their combination to assess the possible improvements in vehicle fuel economy to be obtained by alterations in the transmission design.

4.3.4.3. Effect of Rear Axle Ratio

It is difficult to assess the performance of a transmission without giving equal consideration to the rear axle ratio. While the gear box is used to provide the variation in operating range of the engine, the rear axle ratio is a multiplier over those provided by the gears in the transmission and, hence, it generally plays the role of determining the average rpm speed at which the engine runs. The effect of the change of the rear axle ratio on the reference vehicles can be seen in Table 4-20.

The fuel consumption savings (shown in Table 4-20) which are effected by changing the rear axle ratio were computed by reducing the axle ratio of the reference vehicle by 10%. Reduction in the rear axle ratio permits the engine to operate in a higher loaded condition and at a lower speed, thus enhancing its fuel economy. A reduction in axle ratio means that the engine can run at a lower speed, thus reducing the engine's mechanical friction, and because there is less throttling of the engine, there are less pumping losses as well. However, as seen in Table 4-20 the effect is not very great for the FDC. A change of only about 1% in the FDC fuel consumption was observed for the six reference vehicles. At steady speeds the reduction in rear axle ratio gives a more marked improvement on fuel economy; however, even then only a 4% improvement was observed.

TABLE 4-20

EFFECT OF A 10% REDUCTION IN REAR AXLE RATIO ON FUEL ECONOMY OF REFERENCE VEHICLES
(Basis no greater than 10% performance)

	Percent Fuel Economy Improvement MPG			
Reference Vehicle	FDC %	30 mph %	50 mph %	70 mph %
Co. X – Compact	0.68	4.5	5.0	6.2
Co. X – Standard	0.0	4.7	5.4	4.1
Co. X – Standard with Air Conditioning	0.0	4.2	4.6	4.3
Co. Y – Compact	0.95	1.0	1.0	4.08
Co. Y – Standard	1.25	2.2	4.35	2.07
Co. Y – Standard with Air Conditioning	1.25	3.5	4.50	3.50
Summary	1%	3.5%	4%	4%

4.3.4.4 Effect of Lockup

The effect of adding a lockup device to second and third gear of an automatic transmission torque converter is shown in Table 4-21 below.

TABLE 4-21

EFFECT OF ADDITION OF LOCK-UP IN 2nd AND 3rd GEAR ON REFERENCE VEHICLE X-STD

	% Fuel Economy Improvement					
	FDC	30	40	50	60	70
Lock-up Added	5.4	5.3	5.4	5.4	6.0	3.4

The lockup device used with the torque converter is an improvement aimed at eliminating the losses in the fluid coupling of the torque converter in gears other than the start up gear number 1. At start-up the torque multiplication and slip is important to initiate the car motion and to provide the added torque multiplication needed. However, in higher gears a torque converter lock-up may be used to eliminate the slip losses in the fluid coupling with a small decrement in performance. The loss in performance due to removal of the torque multiplication at higher gears is minor.

While only a 1% improvement in the FDC fuel economy was experienced by the 10% reduction of the axle ratio, a greater improvement in fuel economy could result by the combined addition of lockup and reduction in axle ratio. A 6% improvement in FDC fuel consumption was observed with a vehicle incorporating these improvements. As mentioned earlier the reduction in axle ratio increases the torque handled by the torque converter, thereby increasing the losses across the torque converter. The added torque due to a lower axle ratio and subsequent increase in slip and torque converter losses may be mitigated by the use of a lock-up device. We believe that a lock-up mechanism similar to that developed by Borg-Warner for Studebaker[49] can be developed meeting customer requirements for smoothness during shifting and allow lock-up in all speeds after first speed. Furthermore, the reader is directed to the report prepared by K.B. Hanman and J.W. Schmidt on automatic transmission for off highway vehicles [50] which describes a similar lock-up device.

In summary, the use of a torque converter lockup device as a "stand-alone" improvement can provide substantial improvement in the fuel economy of the vehicle. As part of a composite improvement, including the axle ratio, the torque converter lock-up may provide increased benefit. This is because most improvements of the transmission drive train are improvements intended to lower the engine speed and raise the drive train torque so that the engine operates at minimum specific fuel consumption which results in higher slip losses on an unlocked torque converter. The addition of a torque converter with lock-up permits the alteration of drive train components aimed at increasing the engine torque by eliminating the increased fluid coupling losses that would otherwise be experienced by lower engine speed and increasing engine and drive train torque transmission.

4.3.4.5 Transmission Gear Box

The addition of gears without lockup improves the fuel economy of the vehicle over the Federal Driving Cycle because it permits the engine to operate at lower speeds with higher torques utilizing the more efficient operating conditions of the engine. However, an important side effect from adding a gear to the transmission box is experienced. The reduction in engine speed due to the added gear ratio is accompanied by an increase in torque. At each change in gear ratio the speed ratio across the torque converter is suddenly increased with the higher gear and, as will be discussed in the following section, the torque converter losses increase. Therefore, the addition of extra gears,

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[49] Churchill, H.E., Studebaker Automatic Transmission, SAE Journal, Vol. 4, No. 3, July 1950.

[50] Harman, K.B., and Schmidt, J.W., An Automatic Transmission for Off-Highway Vehicles, SAE Paper 730442, April 3, 1973.

as seen in Table 4-22, while permitting the engine to operate at lower rpm's and increase thermal efficiency, incurs higher losses in the torque converter due to the transmission of higher torques. Without torque converter lockup in gears, the increase in fuel economy with the addition of number of gears is mitigated by the accompanied losses in the torque converter.

TABLE 4-22

IMPROVEMENT IN FUEL ECONOMY EFFECTED BY ADDING GEARS TO TRANSMISSION

(Basis Same Performances and No Lock-up)

No. of Gears*	FDC	% Improvement For 30	40	50	60	70
1	1-3	7	7	8	6	4
2	8-10	15	16	17	15	11
∞	13-16	21	25	26	24	23

*Added to existing reference vehicle gear boxes

4.3.4.6. Torque Converter

As indicated in Section 4.3.4.2 the torque converter is a device which couples the engine to the drive train of the vehicle. It provides a smooth coupling between the power developed by the engine and the torque necessary to drive the gear box and subsequent drive train components.

With the vehicle at rest and the accelerator depressed, power is developed by the engine at the engine crank shaft. This rotary motion must be smoothly coupled to the stationary drive train components in order to give smooth acceleration. This is accomplished by the fluid coupling of the torque converter. Basically the torque converter consists of a fluid pump and a fluid turbine in the same housing. As the engine turns the pump, fluid is propelled across to the turbine causing momentum to be imparted to the turbine blades which is directly coupled to the gear box and drive train components. As the engine speed increases, the pump speed is subsequently increased and the fluid coupling between the pump and the turbine provides for a higher delivery of momentum and increased delivery of power to the drive train components.

The torque converter is a hydraulic machine; its characteristics will be the same under similar flow conditions. A schematic of the torque converter is shown in Figure 4-28a. The ratio of the output speed to input speed determines the fluid flow; the torque ratio will be a function of the speed only. However, the input torque will affect the pumping of the fluid which will, in turn, affect the input speed. This phenomenon is characterized by the "K" value which relates the effect of input torque on input speed. From hydromechanical laws of centrifugal machinery, it can be shown that the input torque (T_1) is proportional to the square of the input speed (N_1) and

$$T_1 \propto N_1^2$$

where the K factor reflects this relationship

$$K \equiv N_1/\sqrt{T_1} = \text{function of } N_o/N_1 \text{ only}$$

Where N_o is the output speed.

Each torque converter will have a relationship of torque and K factor to speed ratio as shown in Figure 4-28b. These two parameters are all that is necessary to prescribe the operation of a torque converter.

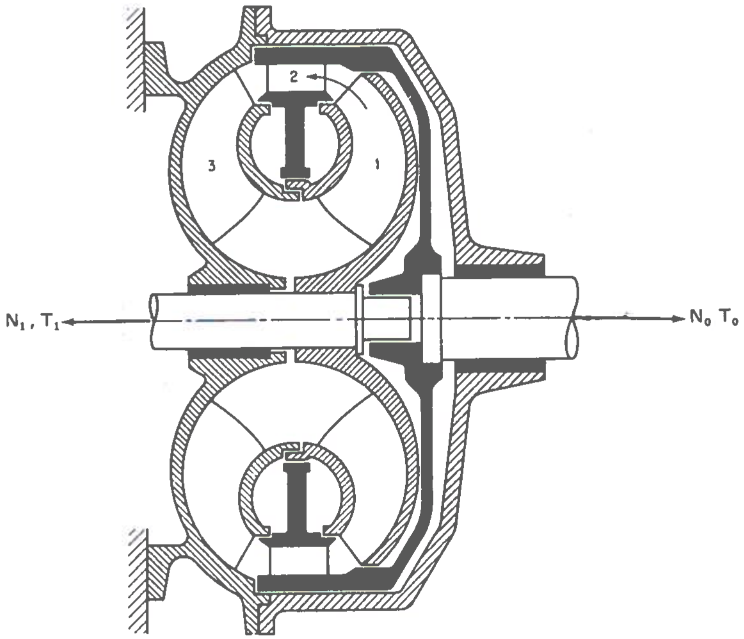
Larger torque converters are capable of handling higher torques, in accordance with the hydromechanical relation for torque

$$T_1 \propto N_1^2 \; D^5 \propto N_1^2/K^2$$

where D is the diameter of the pump-turbine. A larger torque converter permits the handling of higher torques without added engine speed (N_1). On a basis of matching the engine to the torque converter, it can be seen that an improvement in fuel economy may sometimes be gained by using larger torque converters, thereby lowering engine speed. However, too large a torque converter will degrade acceleration because the engine will be too heavily loaded.

It can be seen in the above relationship that a small *overall* K factor means a larger torque converter and higher torque handling capability.

The torque converter responds very much like a centrifugal pump. As the speed input to the pump increases, the torque into the input side of the device increases as the square root of the input speed. Larger sized torque converters are capable of handling larger torques for smaller input speeds. Therefore, a larger torque converter permits the input of higher torques without the cost of higher input speed.



Torque Converter Characterization

Speed Ratio	N_0/N_1
Torque Ratio	T_0/T_1 = function of N_0/N_1
K Factor	$N_1/\sqrt{T_1}$ = function of N_0/N_1

FIGURE 4–28a TORQUE CONVERTER

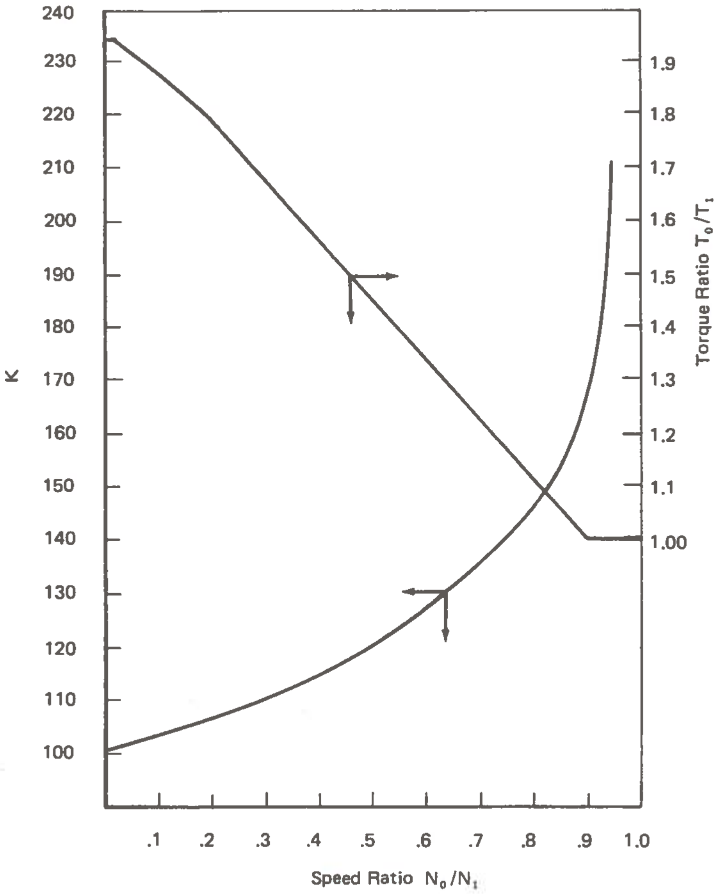


FIGURE 4–28b RELATIONSHIP OF TORQUE AND K FACTOR

For a fixed output horsepower from the torque converter, the speed ratio across the torque converter (the output speed over the input speed) will increase as the size of the converter is increased, or as the K factor is reduced. In general, the efficiency of the transmission of power for the torque converter is directly proportional to the speed ratio. Therefore, a larger torque converter, i.e., one with a smaller K factor, generally can provide more efficient coupling between the input and the output elements.

Table 4-23 shows the effects of a smaller K factor, or a subsequently larger torque converter, on the fuel consumption of two vehicles. The weight of the two vehicles is somewhat different, however. As can be seen in Table 4-23, the effect of a reduced K factor far outweighs the 2% increase in the vehicle weight; therefore, no adjustment has been made for this small factor. There is an approximate increase of 8% in the fuel economy over the FDC and proportionately smaller increases in fuel consumption for the lower K factor torque converter at constant speeds. The reduced effect of steady speeds on the improvement gained by a smaller K factor torque converter is due to the reduced torques handled by the transmission at steady speeds. The FDC includes many accelerations and decelerations which require the transmission of much higher torques through the converter and the subsequent increase in fuel consumption from changing the K factor.

TABLE 4-23

EFFECT OF TORQUE CONVERTER DESIGN ON FUEL ECONOMY

		Fuel Economy in MPG					
"K" Factor*	Vehicle Weight	FDC	20	30	40	50	60
100	5,008	15	21	23.4	23	21	18
115	4,856	13.8	20.4	22	22	20	17
% Gain for K Smaller		8%	3%	7%	6%	5%	5.8%

* The K factor is a non-dimensional number indicating the torque multiplication of the converter. For the same rpm input to the converter, the converter with the lower "K" factor can carry higher torques, but it is subsequently stiffer and may be less smooth during shifting. Converters with lower "K" factors are sometimes referred to as "tight" or stiff"; conversely, converters with high "K" factors are called "loose" or "soft."

4.3.4.7. Transmission Shift Logic

Altering the shift logic of an automatic transmission has been proposed as a means of improving fuel economy of the vehicle. In general, the rationale is that a shift logic which prevents the engine from reaching high rpm's will enhance the fuel economy of the vehicle. An early shift to a higher gear results in lowering the engine rpm, which will reduce the engine friction encountered in propelling the vehicle. On first consideration this scheme appears to be a simple method of enhancing the fuel economy of the vehicle. However, over the FDC which includes may accelerations through all the gears, incorporation of an early shift to a higher gear shift did not substantially enhance the fuel economy of the vehicle. In fact, an improvement in fuel economy of only about 2% was noted. The problem encountered with shifting to a higher gear earlier in an acceleration mode is that the engine must provide the same horsepower at a lower speed; therefore, a higher torque is developed and it has to be transmitted by the torque converter. Without a redesign of the torque converter, the losses thus sustained by the higher torques transmitted by the torque converter tend to negate the improvement in fuel economy realized with the engine operating at a lower rpm. This effect can be seen in Table 4-24 which shows the effect of two different shift logics: (1) a low shift point logic which shifts to a higher gear early in the acceleration, and (2) a high shift point logic which shifts later in the acceleration. Both of these shift logics are incorporated in the same vehicle with and without a torque converter lockup in second and third gears.

The effect of shift logic on fuel consumption with and without torque converter lockup is shown in Table 4-24. The table shows the net consumption by each of the engine and drive train components in gallons of gasoline for the FDC. This breakdown in terms of gallons of fuel consumed is most helpful in understanding the effect of shift logic on fuel consumption. Case 1 is a standard Company X car without lockup and the breakdown for its performance in the FDC. Case 2 is a low shift logic profile without lockup on the same vehicle of the same weight and same engine. The early shift logic of Case 2 shows an increase in the fuel consumed. However, most of the increase is due to the transmission losses. With the low shift logic, higher torques are developed by the engine, and the torque converter – not designed for this shift logic – is responsible for a substantial loss in fuel economy. As might be expected, the accessories consume somewhat less fuel because the engine was running at a lower rpm. Case 3 shows a high type shift logic with an improved fuel economy, contrary to popular belief. This is due to the improved efficiency of the total transmission, primarily because of the lower torque demand placed on the torque converter. The high type shift logic without lockup does not substantially increase engine rpm in this particular case, and thus the accessory mode does not consume much above the standard case. Case 4 shows a low type shift logic with lockup added to the torque converter. The lockup is maintained in second and third gears, while first gear utilizes the torque converter for startup purposes. As seen in this example, the transmission losses are substantially lower, approximately one-third to one-half of the previous transmission losses. The accessory losses are also lower because of the lower engine speed due to the shift logic. Therefore, some improvement in fuel economy may be gained with shift logics so long as lockup is included. This is borne out by the last example – Case 5 – in which a high type shift logic is also used with lockup. This case also shows an improvement over the cases in which lockup was not provided. In Case 5, a high type shift logic, the engine speed is increased and hence the accessories show a greater amount of gallons consumed than in the previous case. The transmission also shows a slight increase in gallons consumed, primarily because, since the torque converter is used in first gear, more time is spent with power being transmitted by the torque converter before second and third gears are engaged when it is no longer used.

TABLE 4-24

EFFECT OF SHIFT LOGIC ON FUEL USAGE (IN GALLONS) OVER THE FDC WITH AND WITHOUT TORQUE CONVERTER LOCKUP

Case	Shift Type	Torque Converters	Accessories	Transmission and Drive Train	Propulsion Aero Rolling Acceleration	Deceleration and Idle	Total Gals. Consumed
1	Standard	No Lockup	.072	.092	.357	.162	.683
			0%***	0%***	0%***	0%***	0%***
2	Low*	No Lockup	.063	.126	.331	.162	.682
			12.5%	(36)	(7.8%)	0%	.2%
3	High**	No Lockup	.072	.086	.358	.162	.678
			0%	32%	(.3)	0%	.7%
4	Low*	With Lockup	.056	.040	.338	.162	.598
			22%	57%	5%	0%	12.4%
5	High**	With Lockup	.062	.043	.359	.162	.626
			13.4%	53%	(.4)	0%	8.3%

*Low = Early shift to higher gear, therefore maintaining lower engine rpm.

**High = Late shift to higher gear, therefore maintaining higher engine rpm.

***% = Percent of fuel usage reduction (increase) over reference vehicle.

In summation, therefore, it is obvious that a great deal of emphasis must be placed on the torque converter and whether lockup is incorporated. Lockup substantially affects most of the improvements that can be gained by changes in the gear box or alterations of the torque converter itself. In addition, changes in the rear axle ratio are also affected by the torque converter if lockup is provided. In all cases, as could be expected, the locked-up torque converter – at least in the higher gears – provided a substantial increase in fuel economy which, on its own, warrants further investigation.

4.3.4.8. Automatic Transmissions versus Manual Shift Transmissions

We did not investigate the potential improvement of the manual shift transmission for the simple reason that we felt that by incorporating a lockup device in the torque converter which, in effect, would eliminate any inefficiencies within the torque converter itself, the net effect would be the same as that of a manual shift transmission. Furthermore, we felt that a manual shift transmission is not acceptable to the consumer and therefore should not be considered.

4.3.4.9. Overdrive versus Four-Speed Transmission

As we have shown, the addition of a fourth speed to a three-speed transmission does improve the fuel economy. The fourth could essentially be an overdrive gear ratio used to properly adjust the total power train gear ratio for the best fuel economy without loss in performance. In discussions with manufacturers of transmissions, we concluded that this so-called overdrive gear ratio could most economically be part of the gear box itself rather than an add-on feature as was supplied during the 1940's and 1950's. The result would be less costly and, in our opinion, amount to no more than $30 to $40 per transmission as an initial cost to the first buyer.

4.3.4.10. Optimum Engine Loading Using A Continuously Variable Transmission

The continuously variable transmission (CVT) might be considered as having an infinite number of gear ratios. The CVT provides a continuous change of gear ratios over the entire speed range of the transmission, permitting the operation of the engine at its most efficient torque and speed operating points. The CVT therefore provides maximum improvement in fuel economy which could be provided as well by an increased number of gears.

As previously discussed a substantial improvement in fuel economy could be achieved if a transmission were available which provided a better selection of engine operating points under all vehicle operating conditions. Figure 4-29 shows a typical engine performance map with BSFC contours. Note that the best BSFC values occur near full throttle at somewhat less than half rated engine speed. A typical operating line for vehicle steady-speed level road load conditions is shown. It does not pass through the region of maximum efficiency due to the requirement of a sufficient acceleration allowance by means of throttle opening alone (no transmission gear changes).

For best vehicle operating economy, it is clear that the operating line should pass through the region of lowest BSFC. Such an "optimum operating line" is illustrated in Figure 4-29. As output power is increased from idle, the engine speed remains constant at some minimum value while the air throttle opening is increased. When the power level reaches that corresponding to the minimum SFC contour, then engine speed is increased, along with throttle opening, in such a manner as to traverse the center of the minimum BSFC island, as shown in Figure 4-29, until the full throttle condition is reached. Thereafter, the engine speed alone is increased to the maximum value, thereby yielding maximum horsepower. To achieve this optimum operating line in practice, it is necessary to have a continuously variable ratio transmission and suitable control system so that the most desirable engine speed can always be selected independently of the vehicle road speed. The speed ratios R (transmission input speed ÷ output speed) required to traverse this ideal operating line are designated at various points along the line. For the engine and vehicle system illustrated, the required speed ratios range from 0.61 to 1.11. If this ratio range is excessive for a practical transmission, the operating line can be modified slightly to reduce the speed ratio but still pass through the most favorable BSFC region.

The two principal types of continuously variable transmissions are the traction type and hydraulic (hydrostatic or hydromechanical).

4.3.4.10.1. Traction Transmissions – One development activity in traction-type, continuously variable transmissions was the subject of a field trip and resulted in the acquisition of performance data that were used in the computer simulation studies.

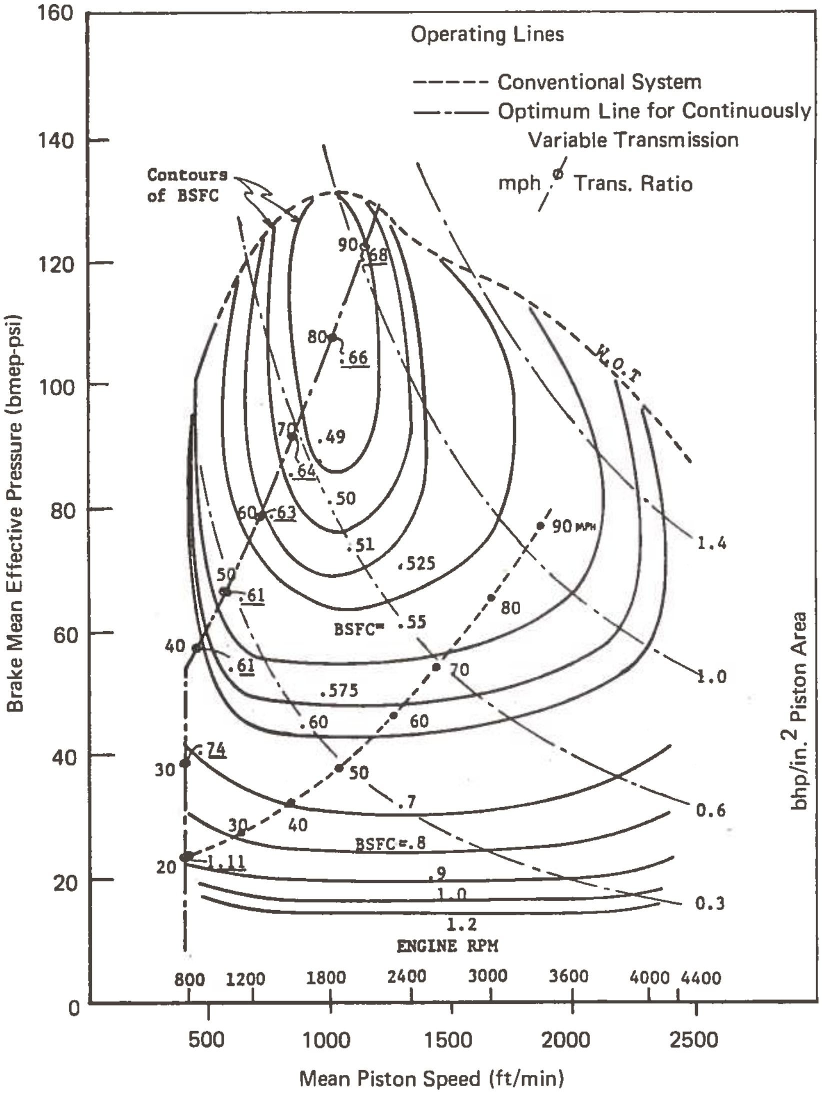


FIGURE 4–29 PERFORMANCE MAP – TYPICAL GASOLINE ENGINE (300/in.^{3} V-8)

Tracor, Inc., of Austin, Texas, is engaged in the development of a dual-cavity, toroidal-type traction transmission which is suitable for automotive use. The unit is described by J. Kraus[51] and C. Kraus.[52] Their general findings are summarized below.

The Tracor traction transmission (CVT) is in an advanced state of development. Significant advances in durability, efficiency, and response seem to have been made over the G.M. toroidal drive and other similar units. The Tracor double-cavity unit is capable of operation over a ratio range of 9:1 with an extremely fast ratio change response (full ratio range change in 8-10 revolutions). It is claimed to have a very good efficiency characteristic (exceeds 90% over most of the operating range). Tracor claims a size, weight, and cost equal to or less than conventional three-speed automatics. Besides allowing engine operation at higher BSFC values, the CVT can provide improved vehicle acceleration performance by smoothly and rapidly increasing engine speed during acceleration manuevers. This permits using an engine of smaller displacement and realizing further benefits in fuel economy. Kraus[43] claims that this transmission provides a 25-30% increase in mpg and about 30-50% better acceleration compared with the same car equipped with equal engine horsepower and a four-speed manual transmission. When we compared and simulated the ideal traction transmission car with that of a standard car with higher engine power to provide equal acceleration performance, the fuel economy of the traction transmission car was about 19% greater than that of the reference vehicle for the Federal Driving Cycle and about 30% greater for the highway driving fuel economy.

4.3.4.10.2. Problem Areas – Opposing these substantial benefits are the following problem areas associated with the CVT.

1. Improvements in BSFC are obtained by operating the engine at a higher load factor (greater BMEP), thereby increasing the durability requirements. The engine to be used with a CVT will therefore require a complete redesign and development with a larger and heavier structure to provide the needed durability at the higher average BMEP values. Additional cost and weight could become prohibitive.

2. Good acceleration performance would be attained by allowing high engine speeds during WOT accelerations. This would result in a substantial increase in engine noise level during accelerations. There is some question whether the added noise level would be acceptable to the customer as the price for improved fuel economy.

3. The CVT transmission will be constantly changing in ratio in response to changing driving conditions. Therefore wear and durability of the transmission mechanism poses a potential problem whose solution has not yet been demonstrated.

4. We also feel that a substantial development program is required to design and build a suitable control system that will properly signal the input to the transmission in response to the driver demands. Such a system would automatically provide the best fuel economy for the best performance based on the input.

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[51] Kraus, J.H., Traction Drive Shows Automotive Promise, Machine Design, October 18, 1973.

[52] Kraus, C.E., and Gres, M.E., New Hope for the Single-Shaft Turbine Car, Gas Turbine International, May-June, 1973.

5. At the present time the Tracor transmission is in the development stage and, while it is reputed to have performed quite well in a vehicle, we were unable to test the vehicle ourselves so we are unable to comment on response of the transmission to the engine. We understand the vehicle was inoperable, not because of the transmission itself, but instead because of the fluids used in the transmission, which apparently were foaming and causing surging in the control system. If a fluid suitable for a transmission of this nature is not found, then further investigation would have to be made on the development of the required fluid. We consider the development of such a fluid to be beyond the normal scope of a transmission developer and therefore would require the combined efforts of the transmission developer and a company which had expertise in hydraulic systems and fluids. We suggest this concept be developed further.

Despite these problem areas, the large potential benefit in reduced fuel consumption makes it attractive to pursue the development and possible future introduction of this type transmission. To simplify the evaluation it was based on an assumed 90% transmission efficiency over the entire operating range based on the information from Figure 4-30. Computer simulation results agree reasonably well with those claimed by Kraus.[51]

While this transmission appears to be promising, we feel the time scale needed to accomplish the total development and engine matching program would run to the early 1980's before production cars could be sold.

4.3.4.11. Hydromechanical Transmission

The Orshansky Corporation is designing and developing a multirange hydromechanical transmission for use in passenger cars. As designed it could handle 175 lb-ft of torque at 4000 rpm. The overall ratio of the transmission will be 0.588 overdrive to 3.30 reduction. While this development has just started with hardware expected to be available next year, it is based on a great deal of background analysis and computer simulation work by the Orshansky organization. The firm is also responsible for having designed and built a transmission for a large John Deere tractor and a racing car.

During our field visit to Orshansky, the tractor was demonstrated and operated smoothly. It had a single lever which enabled the driver to go from low to high range and even into reverse with the engine running at constant speed. The firm is also designing, developing, and building for a large truck manufacturer a truck transmission which will be ready late in 1974. Because of these developments and the analytical work that Orshansky has performed, we felt it wise to include this transmission as a potential for fuel economy gains in the passenger automobile.

On first examination the transmission appears to be complex using both hydraulics and mechanical systems to provide the multirange, continuously variable drive ratios. However, the hydromechanical transmission consists of components of proven reliability, having been adapted from automotive and industrial transmissions which have had a long history of commercial use and

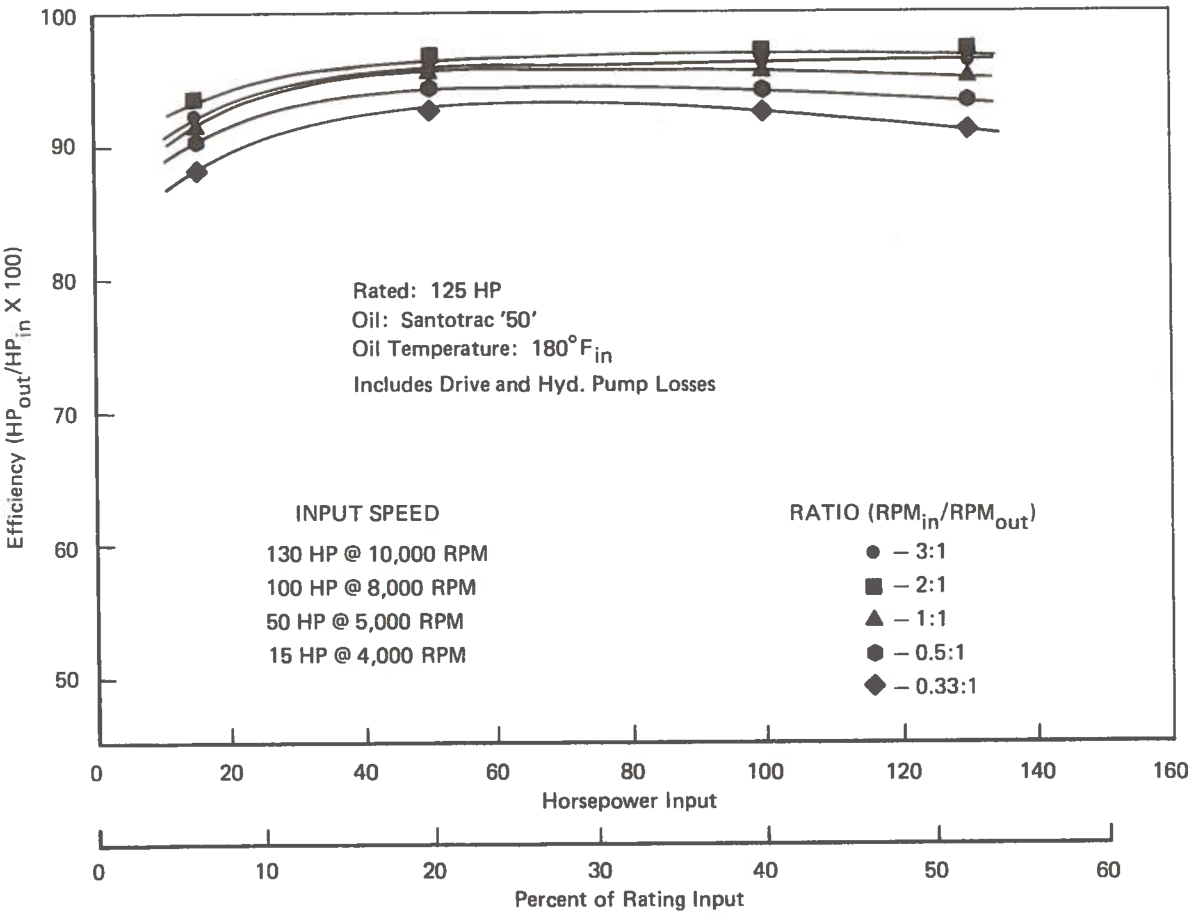

FIGURE 4–30 TYPICAL EFFICIENCY CURVE FOR TRACOR TRACTION DRIVE-PROPOSED HIGH-EFFICIENCY AUTO DRIVE – COMPUTED EFFICIENCY DATA

service in the power ranges required. Therefore, the problems in the use of this transmission are not caused by the individual components making up the transmission, but more by the manner in which they are combined to provide the continuously variable speed ranges.

The Orshansky hydromechanical transmission is a split power path-type device which transmits a portion of the power through a direct mechanical path and a portion of the power through a positive displacement hydraulic motor pump. The efficiency of this transmission purportedly remains high because a major portion of the power is transmitted through mechanical devices inherently high in efficiency, and because the portion of power that is transmitted through the hydraulic motor pumps is low compared to the other. Therefore, the total efficiency of the transmission is comparable to the standard automatic transmissions in automobiles today.

In the past the low efficiencies of hydromechanical transmissions over a wide range of torque-speed variation was the chief reason why they were not used in automobile applications. A second problem involved the transmission noise caused by the hydraulic units. However, this new unit developed by Orshansky proves that this problem can be overcome by the proper design. Thirdly, the development of stable and reliable control systems that will enable the engine and transmission to operate under optimum conditions, regardless of the low load or speed of the vehicles, is also a problem.

From the computer simulation program performed by the Orshansky Corporation, they were able to show a fuel economy improvement of approximately 30 to 35% for a typical American-made full-sized sedan operating over suburban and city driving conditions. The performance of the automobile was the same as the conventional car to which it was compared. Because of this performance, we have included this transmission in the study as a potential for fuel economy improvements. Table 4-25 was provided by the Orshansky Corporation and shows the computer-simulated comparison between a hydromechanical continuously variable transmission with a conventional automatic transmission both operating in vehicles having the same 300-cubic inch engine. We assumed that the acceleration time of 0 to 60 mph was roughly the same for both applications.

The Orshansky Corporation presently estimates that the cost of the transmission would be approximately the same as that of present-day automatic transmissions, and layout drawings indicate that its size and weight would be roughly the same as well.

Since this transmission is in the early state of design, we anticipate that its application to production automobiles would not be possible prior to the early 1980's. For the reason stated in the discussion on the Tracor transmission and those particular to the Orshansky transmission, we would consider this approach now to have a high degree of risk, primarily because of the development problems that should be expected with a device in this early state of development, particularly in view of the problems that might be encountered in matching it with a heavy duty engine.

TABLE 4-25

SIMULATED DRIVES COMPARING A HYDROMECHANICAL CONTINUOUSLY VARIABLE TRANSMISSION WITH A CONVENTIONAL AUTOMATIC TRANSMISSION*

Vehicle Weight	Hydromechanical Transmission 4463	Conventional Automatic Transmission 4433	Percent Change
City Driving – (Not F.D.C.)			
Miles per gallon	12.45	10.63	+17.1
Oxides of nitrogen (gm/mile)	5.40	6.23	- 13.3
Hydrocarbons (gm/mile)	0.567	0.548	+ 3.5
Carbon monoxide (gm/mile)	20.5	25.7	- 20.2
Suburban Driving –			
Miles per gallon	21.07	17.41	+21.0
Oxides of nitrogen (gm/mile)	4.63	4.40	+ 5.2
Hydrocarbons (gm/mile)	0.327	0.304	+ 7.6
Carbon monoxide (gm/mile)	4.53	10.5	- 57.0

*Both vehicles had the same 300+ Cu. In. engine. This simulation was performed by the Orshansky Transmission Corporation, N.Y.

4.3.5. Automobile Accessories and Auxiliaries

4.3.5.1. Background

A small, but significant amount of mechanical power generated by the automobile engine is used to drive a set of accessories which are coupled through flexible Vee belts attached to pulleys on the front end of the engine crankshaft. All accessories absorb usable power from the engine, thus creating a gasoline mileage penalty. These accessories may be classified into three categories:

1) Accessories which are necessary for operation of the engine and/or motor vehicle –

Water pump
Fan
Alternator
Oil pump
Ignition system

2) Accessories which are added to meet environmental requirements –

Air pump

3) Accessories which are for the convenience of the driver as necessitated by the vehicle size or the local weather conditions –

Power steering pump
Air conditioning compressor

The oil pump used in all engines and the distributor used in spark ignition engines or the injector pump used in diesel engines were not considered in this study, because all are required for the operation of the engine and are low power consumers.

Accessories are designed to reliably satisfy a particular level of performance, to be inexpensive to manufacture, and to be of minimal size and weight. In most cases, the design of an accessory is determined by a "most severe" condition, so that adequate performance is always ensured. This means that under less demanding operating conditions, the accessory may run inefficiently, wasting valuable power.

The objectives of this assessment of the power absorbed by accessories are to:

1) Determine the demand load characteristics on each accessory,

2) Assess technologies for matching the operating characteristics of individual accessories to the demand requirements, and

3) Assess the engineering and manufacturing feasibility of attractive design alternatives.

4.3.5.2. Methodology

The methodology we used to assess automobile accessory designs included:

1. Describing the principles and operation of each of the present standard accessories outlined above;

2. Discussing the design considerations important to the accessory construction;

3. Formulating a physical model for use in quantifying the power required of the accessory; and finally

4. Assessing alternative devices within current technology which reduce the power requirements of the accessory from the engine, while at the same time meet an accepted level of accessory performance.

4.3.5.3. Analysis of Accessories

4.3.5.3.1. Water Pump – Of the total energy used by the automobile engine, approximately 20% is lost as heat transferred to the metal cylinder block. This heat must be removed from the engine to prevent damage from the excessive temperatures. In small four-cylinder engines, air cooling may be sufficient or, as in the case of the early Ford Model T engine, natural thermal siphon may also be sufficient. However, in large modern engines a circulating water cooling system is required. In such a system, water is pumped through a cooling jacket surrounding the cylinders where heat is transferred from the engine block and heads to the water and then through a radiator where the heat is transferred from the water to the ambient air.

Centrifugal pumps are universally used in cooling systems because their flow rate is proportional to engine speed, and they are inexpensive, reliable, and allow a cooling system to thermosiphon when the engine is turned off, thereby providing some natural water convection for cooling. In current designs, the water pump is driven directly by a belt attached to the engine's crankshaft pulley, and the pump's speed increases in direct proportion to the engine's speed. The thermal load on the cooling system increases with engine speed and the cooling circulation also increases with engine speed. Therefore, the demand and the availability of water circulating capacity in the water pump are in balance. Thus, the power required to drive the water pump, as shown in Figure 4-31, cannot be significantly reduced.

4.3.5.3.2. Cooling Fan – The primary function of the cooling fan is to draw cool air in through the radiator and blow it back over the engine and exhaust pipes during periods when there is insufficient air supplied by the forward motion of the vehicle. The increasing cooling load at increased engine speeds indicates the need for increased air flow through the automobile radiator. Air flow is provided by the cooling fan and the vehicle forward speed. As shown in Figure 4-31, for a vehicle moving forward at road speed, ram air enters through the front grill and onto the radiator face. This ram air effect creates a pressure head proportional to the square of the vehicle's speed. The fan, situated immediately downstream of the radiator, lowers the pressure on the downstream face of the radiator. The difference in pressure between the front and rear of the radiator core provides the driving force necessary to move air flow past the radiator cooling fins. Usually the fan draws air through the radiator only within the area defined by the fan diameter. A shroud is often fitted around the fan diameter to help draw air through the remaining radiator area. The power required to drive the cooling fan is shown in Figure 4-31.

The effect of fan characteristics is shown in Figure 4-32. When the vehicle is idling, there is no ram air and all the flow is drawn through by the fan and the fan is said to be underfed. At low vehicle speeds, the fan is still utilized to develop flow through the radiator. At high speeds, the fan is overfed as there is sufficient ram pressure to provide all of the coolant flow required through the radiator, and actually the fan is not needed. At low speeds the fan is needed to provide adequate cooling, but at high speeds the ram air itself is sufficient. Thus, the power used by the fan above approximately 2000 rpm's (see Figure 4-31), represents excessive power consumption and is wasted power.

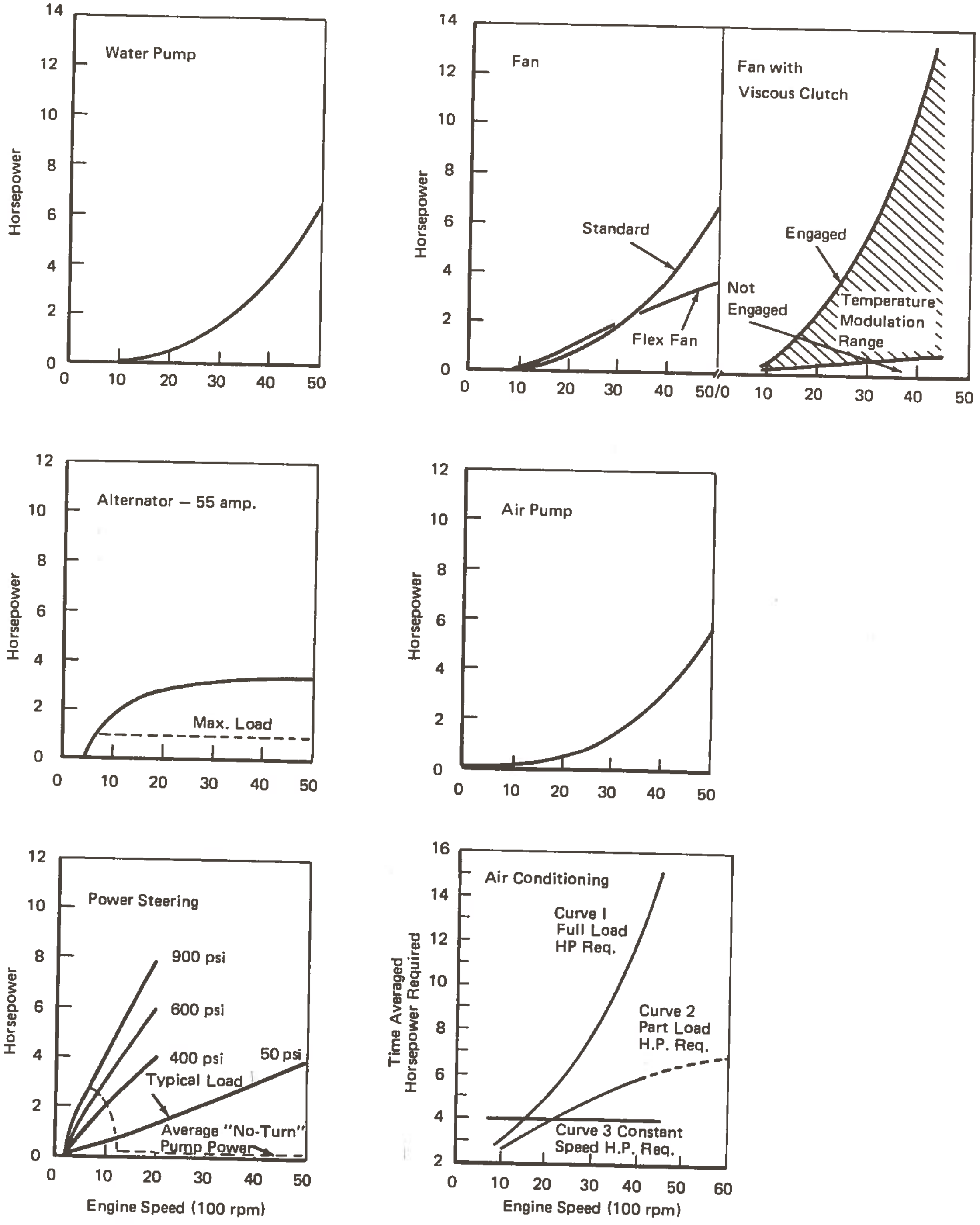

FIGURE 4–31 POWER REQUIREMENTS FOR ACCESSORIES IN STANDARD-SIZE CAR

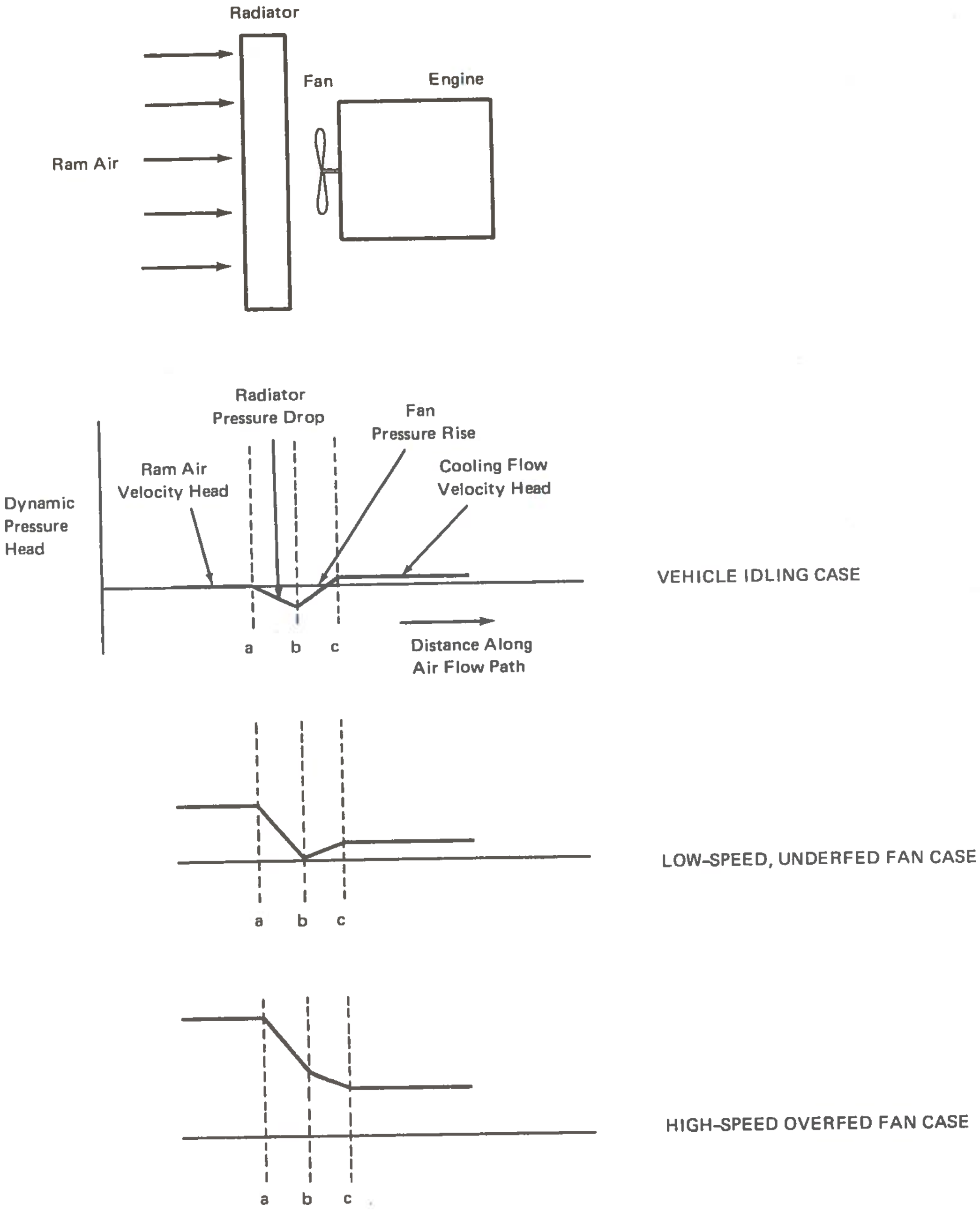

FIGURE 4–32 MODES OF FAN OPERATION

Significant reduction in fan horsepower at high speeds is possible by the use of a viscous clutch fan drive. A viscous clutch provides maximum fan performance at low speeds and reduces noise and horsepower consumption at higher speeds by lowering the fan-to-engine speed ratio. The viscous clutch fan drive usually has a temperature-sensitive control which senses the temperature of the cooling system and varies the fan-to-engine speed ratio according to actual cooling requirements. The range of operation of a typical temperature-modulated viscous clutch and fan is shown in Figure 4-31. The upper limit on the temperature modulation range is the performance curve for a non-temperature-modulated clutch.

An alternative scheme for reducing fan power at high engine speeds involves the use of four blades which have variable pitch control. These fan blades will decamber with increasing speed, thus requiring less power. The characteristics of this flexible type of fan are shown in Figure 4-31.

The cost of a fan without a special drive would of course, be lower. The fan with a viscous drive and/or temperature modulation has a much higher initial cost, and it is presently available and in operation on most cars equipped with air conditioners. We estimate the flexible decambering fan would cost the same as conventional fans and therefore represents a potential low-cost solution to the high powered requirements of fans at high speeds. Flexible decambering blades are not generally available, but their technical feasibility has been demonstrated and, in our judgment, will be used in increasing numbers in the very near future with low risk. Flexible decambering fans are generally available through aftermarket suppliers, particularly in the western states.

4.3.5.3.3. Alternator – The alternator is an AC electric generator used to charge the battery and supply power to the automobile's ignition, lights, and other accessories. The alternator has almost universally replaced the DC generator, principally because of the alternator's high output at low speed, simplicity of manufacture with use of less critical copper components, and the advent of low-cost, solid-state rectifiers.

The alternator converts mechanical shaft power, typically provided by a Vee-belt drive, to electrical power by rotating a magnetic field past a set of fixed coils. The rotating field is produced by either permanent or electromagnets, the former having the advantage of eliminating brushes and containment of high-speed rotating windings in the rotor. At low speeds, the current produced by an alternator is proportional to speed but levels off at high speed due to the inductance of the stator coils. The AC voltage generated is rectified to produce DC power compatible with the battery and the automobile's electric system.

The power required to drive an alternator increases rapidly at low speeds and then very slowly at higher speeds, thus not incurring an excessive power penalty as shown in Figure 4-31. When the load is reduced, excess current charges the battery which, in turn, is used to start the car and help meet extraordinary electric power demands. The alternator must be regulated when the load is satisfied and the battery is fully charged to prevent damage to the battery and the electric system. The charging voltage is maintained at a maximum of about 13.5 volts by reducing the alternator's magnetic field in one of two ways:

a. In alternators with rotating electromagnets (the most commonly used alternator), the field is regulated by reducing the field current; and

b. In permanent magnet alternators, power is fed into secondary coils to produce an opposing magnetic field in the stator assembly, thus reducing the output of the alternator.

The load requirements on an alternator are independent of engine speed. In a 13.5-volt system, a steady load of 45 amps represents a load of approximately 0.8 horsepower as noted in Figure 4-31. The difference between load and actual shaft horsepower requirements of the alternator is the result of conversion efficiency from shaft horsepower to electrical power (approximately 70%) and windage losses associated with the non-streamline shape of the rotor and the windage loss from the cooling fan attached to the front of the alternator. Little need be done to improve the efficiency of the shaft-to-electrical conversion of an alternator. However, a marginal improvement might be possible by eliminating the cooling fan and streamlining the rotor of the alternator. Cooling must be provided for the alternator. It can be effected from air ducted from the low end of the radiator through the stator windings and around the rotor in much the same way that cooling air is ducted around aircraft generators. In addition, the incorporation of a constant-speed drive on the alternator would, at most, save 1 horsepower which we feel is not worth bothering with at the expense of an increase in drive complexity.

4.3.5.3.4. Air Pump – The air pump is a recently added accessory which provides air for injection into the exhaust manifold for post-discharge oxidation of unburned hydrocarbons which might otherwise be exhausted into the atmosphere. We feel that the air pump is a transient accessory which, as engines engender less unburned hydrocarbons, will eventually no longer be required.

The air pumps typically used in present-day automobiles are positive-displacement vane pumps which provide an increasing volume of air with increasing engine speed at a pressure of only a few psi necessary to overcome the exhaust gas overpressure in the exhaust manifold. At normal operating engine speeds (up to 3000 rpm) the pump power is less than 2 horsepower as shown in Figure 4-31. Above this engine speed, the power requirements of the air pump increase significantly.

4.3.5.3.5. Power Steering Pump – The maneuvering of large automobiles, expecially at low speeds, requires levels of force applied at the steering wheel which are higher than a normal driver would be expected to provide. The purpose of the power steering accessory is to give the driver a hydraulic power assist in turning the front wheels, principally when at rest or at low speeds. The power steering unit is capable of providing fast, stable response to steering wheel commands, high output steering forces, and also can feed back the road reaction forces so that the driver can maintain a "feeling of the road." The system is foolproof, with an automatic manual override for safety in case of system failure.

The most widely used power steering system utilizes a pilot-controlled, open-centered control valve which is attached to the steering wheel mechanism to control the flow of high pressure hydraulic oil to a double-acting power piston unit which transmits motion to the steering linkage mechanism. Since the control valve is open-centered, a steady flow of hydraulic oil is used, even when the vehicle is traveling in a straight line. This type of valving, which is inexpensive and immune to dirt problems, utilizes a steady flow of oil for cooling and has good damping characteristics.

The constant flow of hydraulic oil is provided by a positive displacement pump connected to the crankshaft pulley of the engine with a Vee-belt drive. The pump is provided with a flow control relief valve and is designed to provide adequate turning forces for parking while the engine is idling. Highest forces are developed in the steering unit during parking maneuvers and the pump, being directly driven by the engine through a Vee-belt drive, produces its minimum flow at engine idle. The parking situation is therefore the most severe case design point. At higher road speeds and faster engine rpm's, the pump produces excess flow which is bled off through the flow control valve.

The demands upon the power steering system are shown in Figure 4-31. At low engine speeds, typical of parking situations, as much as 3 horsepower are required and, as the speed increases, less power is required on an average for the down-the-road (no turn) power requirements. Superimposed on the power requirements of the steering are the operating characteristics of the pump at the various required pressures. Thus, only at speeds above about 2500 rpm is there much of a penalty paid for the inclusion of a power steering pump. The horsepower-on-demand characteristics of the power steering pump and the small penalty paid (approximately 1 horsepower at engine speeds of 3000 rpm's) do not warrant modifying the system to reduce the power requirements. An alternative might be to eliminate the need for power steering by modifying the steering geometry to reduce the forces required for turning the vehicle when parked. Larger steering wheels and higher gear ratios are another possibility for eliminating the need for power steering.

4.3.5.3.6. Air Conditioner – The automotive air conditioner is designed to provide cooled and dehumidified air to the passenger compartment of the vehicle. The design of the automotive air conditioner is similar to that of the small stationary room air conditioner. The air conditioning system consists of a compressor driven through a Vee-belt attached to the engine crankshaft pulley, a condensor located in front of the engine radiator and cooled by the fan, and an expansion valve and evaporation heat exchanger in which the air for the passenger compartment is cooled. The compressor accounts for more than 90% of the total power consumption of the air conditioning system, consuming as much as 10 horsepower at high engine speed (see Figure 4-31). Therefore, the compressor draws the greatest attention in this analysis of where power may be conserved in the air conditioner.

The air conditioner must provide cooling to meet three major load requirements: (1) the idle at low engine rpm, (2) high-speed driving, and (3) cool-down. During idle, the air conditioner must be able to remove the heat conducted into the passenger compartment as a result of solar energy absorbed by the car and from high outdoor temperatures. At high speeds, infiltration of ambient air provides an additional load on the air conditioner. As the speed of the vehicle increases, air is forced from the outside into the passenger compartment. It is estimated* that about two complete air changes per minute may occur in a standard size automobile. With the air conditioner designed to meet the high-speed driving air conditioning load, the cooldown capacity at start-up will be determined by the idle speed capacity of the air conditioner. Lower air conditioning capacities mean longer pulldown times. The air conditioner must be designed to meet road speed air conditioning loads, while the cooldown capacity is a secondary design criterion.

Two major types of air conditioners exist today: (1) the year-round climate air conditioner which provides temperature and humidity control throughout the year, and (2) the standard air conditioner which is designed for use on demand. The year-round climate conditioner utilizes the compressor even when outside temperatures are below 70°F. This permits the dehumidification of the air which is then subsequently reheated to approximately 72°F. At an outdoor temperature of about 40°F, the year-round climate conditioner control disengages the compressor since humidity control is no longer necessary. Some demand air conditioners use a thermostatically controlled clutch which is regulated by the air temperature of the passenger compartment. However, most standard air conditioning compressors remain engaged during normal air conditioning operation.

Typical full load power consumption of these two types of air conditioners is shown in Figure 4-31 (curves No. 1 and No. 2). The figure shows the time averaged horsepower requirement for the two different types of air conditioners. In actuality there is no change in the compressor and air conditioner design. When the clutch-engaged air conditioner is running, its actual horsepower consumption will be the same as the upper curve for the year-round climate air conditioner. However, studies indicate that for a full sized car, the cooling demand rarely exceeds 2 tons of air conditioning as shown in Figure 4-32a. There is an excessive amount of cooling met by the continuously engaged air conditioner and the clutch-operated air conditioner shows a long-term time average horsepower savings.

Figure 4-32b shows the horsepower requirement per ton of cooling for a compressor operated with R-12 refrigerant at a variety of compressor speeds. It can be seen here that the efficiency of the compressor is reduced by almost a third over the speed range shown. Therefore, if the compressor were held at a constant speed by a constantly variable gear between it and the engine flywheel, then the compressor could deliver approximately a ton of cooling for 2 horsepower delivered by the engine. At maximum cooling demand of 2 tons for a standard sized car, the constant-speed air conditioner power demand could be reduced to 4 horsepower. This is shown in Figure 4-31 (bottom right) as the constant-speed horsepower requirement – curve 3. However, since the constant-speed air conditioner supplies 2 tons of cooling independent of engine speed, it also exceeds the projected demand at low speeds; but this can be avoided by use of a clutch which disengages the drive when the air conditioning demand is met.

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* In S.A.E. Paper 660388, Body Aerodynamics and Heater Air Flow, Shirk states that 200-300 cfm leakage rate at 1" water pressure is current level. A 100 cubic foot interior would experience two changes per minute, at 60 mph for which the static pressure is 1.8" of water.

Such constant-speed devices have been proposed and prototypes are available. One model uses a traction drive with a variable rolling radius to provide the required constantly variable speed ratio. The manufacturer advertises approximately a 90% transmission efficiency and, through proper controls, the unit is capable of generating a constant-speed/constant-horsepower input to the automotive air conditioner compressor. The cost for such a device is estimated by the developer (Tracor, Inc.) to be approximately $25.00 (initial cost to consumer). Such a constant-speed drive can provide some savings in power consumption. At very high speeds (4000 rpm) a constant-speed drive can provide more than a twofold savings in power. However, at engine idle speeds, the power requirement will be higher than for a standard air conditioning compressor drive. There is an added space requirement when a constant-speed drive device is used on the air conditioning compressor. Both the added weight and the cost of the constant-speed device represent large penalties to pay for increased compressor efficiency throughout the total range of vehicle speed. The Appendix includes information supplied by General Motors that a 2-speed accessory drive used in place of a constant speed drive predicts that for their range of models and testing procedures the range of fuel economy improvement would be .9% to 4.8% plus an additional improvement of 2% if other devices such as cycling clutches, reduced compressor size, etc., were incorporated.

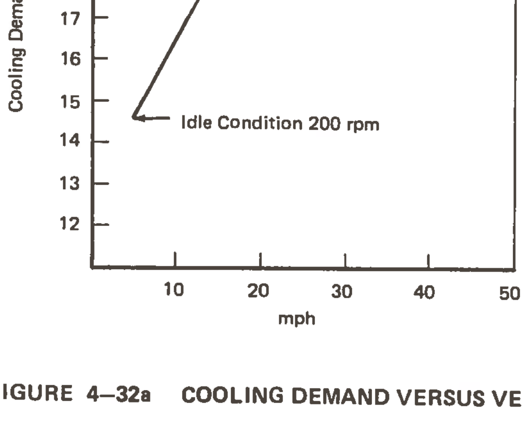

FIGURE 4–32a COOLING DEMAND VERSUS VELOCITY

[1] Conditions: R-12 Refrigerant
R = 5.26; 57 to 300

FIGURE 4–32b COMPRESSOR EFFICIENCY AS A FUNCTION OF SPEED

4.3.5.4. Summary of Accessories Power Requirements

Figure 4-33 shows several summary curves for standard sized automobiles with various combinations of accessories. On the left hand side of the figure are summarized accessory requirements for typical present-day production vehicles. The standard automobile with the basic accessories water pump, standard fan, alternator, air pump, and power steering pump consumes up to 8 horsepower from the crankshaft pulley at normal operating speeds (less than 75 mph). The comparably equipped automobile with air conditioning and a temperature-modulated viscous clutch fan may consume a maximum of between 14 and 18 horsepower at the same maximum vehicle speed. Within the normal driving range, a small savings is effected through the use of a flex fan as shown in the left hand side of the figure.

Through the incorporation of a constant-speed drive on the air conditioning compressor, it is possible to effect a decrease in power consumption above about 25 mph, but at a slight increase at speeds below 25 mph. At the maximum driving speed (75 mph) the total accessory load for the standard size automobile with air conditioning driven by a constant-speed drive is in the range of about 11 to 15 horsepower.

The point must be made that the yearly duty cycle of an air conditioner might very well be 50%, considering cool spring, fall, and winter night driving, and some cool daytime driving. The computer simulation runs show that with all accessories operating at full load, the possible improvement resulting from substituting the conventional drive with a constant speed drive would improve fuel economy (mpg) by 3-7%. If this were factored by the yearly duty cycle, the range would more nearly be an improvement of 1-3% in mpg, because accessories, in our opinion, are run only a third of the time at full load. The added weight for the air conditioning system would carry a fuel penalty cost of approximately $2-4.00/year with gasoline @ 75¢/gal.

4.3.6. Fuel Economy and Tire Performance

Tire performance is an important element in the overall assessment of fuel economy of automotive vehicles. At normal steady speeds below about 50 mph the tires may account for more than 50% of the total power necessary to sustain the vehicle's speed.[53,54,55] Therefore, careful consideration of the tire design and materials of construction can lead to improvement in the vehicle fuel economy.

There are three common types of tires available – bias, bias-belted, and radial tires. The effect of the tire design variation on the power necessary to propel the vehicle at a constant speed is given in Figure 4-34. The clear advantage of the radial at moderate speeds can be seen in the improved rolling resistance over the other two common types of tires. At vehicle speeds up to about 40 mph the radial tire may provide as much as a 30% improvement over the bias tire. Over the entire speed

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53. Elliott el al, Passenger Tire Power Consumption, SAE Paper 710575, June 1971.
54. Curtiss, W.W., Low Power Loss Tires, SAE Paper 690108, January 1969.
55. Floyd, C.W., Power Loss Testing of Passenger Tires, SAE Paper 710576, presented at the Mid-Year-Meeting, Montreal, Quebec, Canada, June 7-11, 1971.

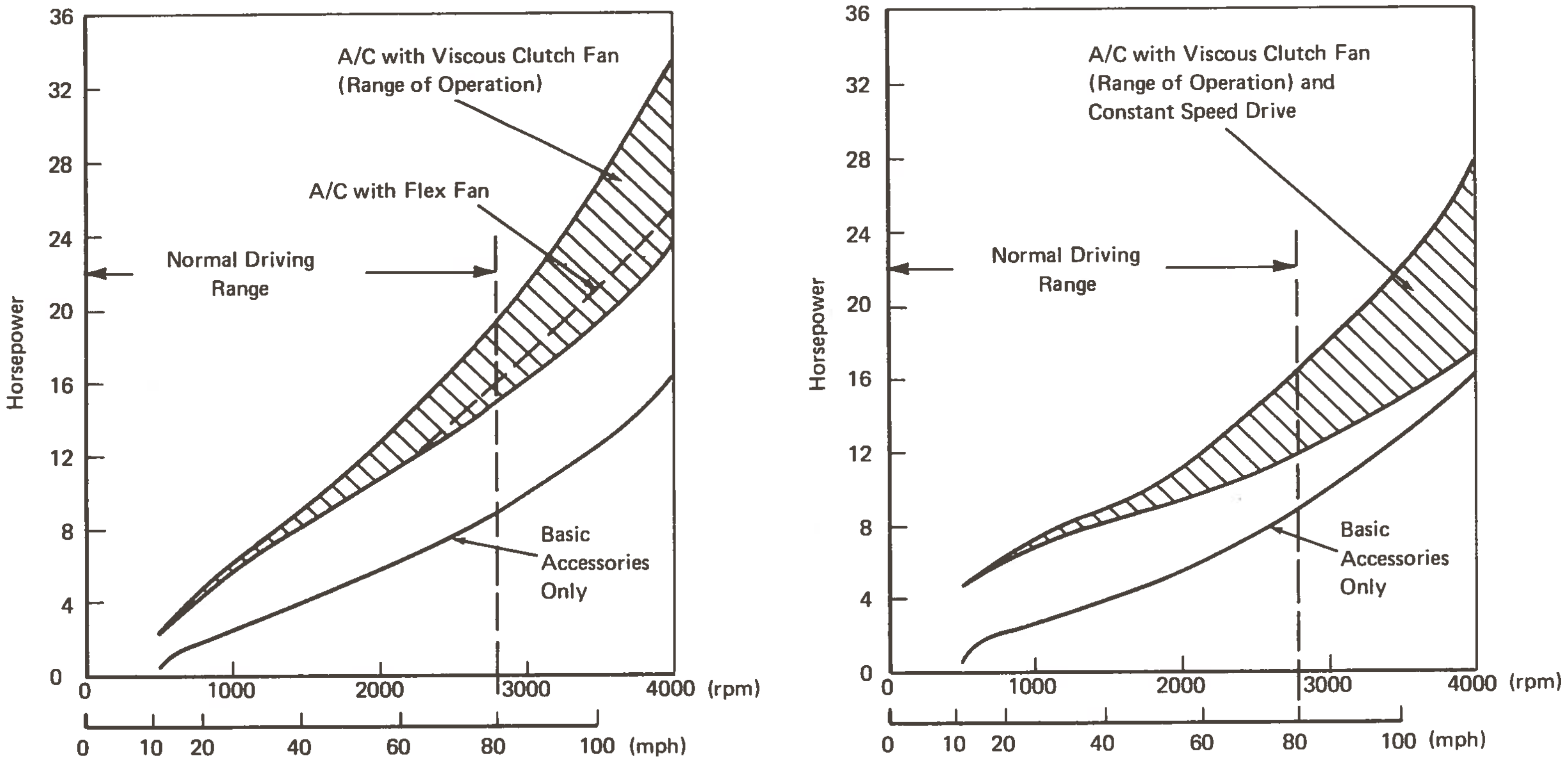
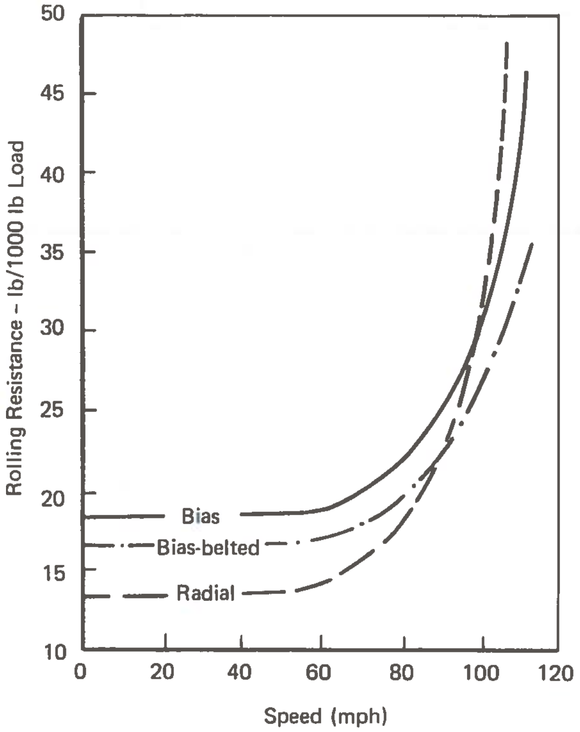


FIGURE 4–33 SUMMARY OF ACCESSORIES POWER REQUIREMENTS – STANDARD-SIZED AUTOMOBILE WITH BASIC ACCESSORIES (Water Pump, Alternator [55 amp], Air Pump, Power Steering Pump, Standard Fan)

Generated From ADL Data.



Source: Elliott, D.R., Klamp, W.K., Kraemer, W.E., Ref. 53.

FIGURE 4–34 TIRE DESIGN VARIATIONS

range of 0 to about 80 mph the radial tire may provide an approximately 10% improvement over the bias-belted tire and then accordingly higher improvement over the bias tire. However, the variations among tire designs may be overshadowed by the variation between tires of precisely the same design using different materials of construction, or other variations in the design of the tire. Such variations include the carcass angle, belt angle, belt width, and tread weight and design. In addition, important environmental factors, such as tire temperature, load, and inflation pressure, have a strong influence on the rolling resistance of the tire.

Under carefully controlled laboratory conditions, the variation between the generic tire design of the bias, bias-belted, and radial tires can be assessed. Elimination of the tread, tread weight, carcass angle, and other tire parameter effects on the rolling resistance have been considered in Curtiss' paper[46] on low power loss tires. In general, it can be stated that the radial tire does provide improved tire performance at most speeds encountered by the average American driver. A summary of the effect of radial tires on fuel economy as compared with the bias ply tires used on the 1973 reference vehicles is presented in Table 4-26. These results were determined by computer simulation, assuming that the radial tires provide a total rolling resistance about 15% less than obtained by bias ply tires.

We consider this innovative improvement to have a very low technical risk, with no major problems involved except those involved in the expansion of production facilities if used on 100% of the automobiles produced. There is a requirement for the change in the chassis, the spring height, shock absorber, calibration, engine and body mount tuning. These factors are already being considered by the automobile industry and an increasing number of new cars being produced will have the radial tires. In a study[56] performed by Arthur D. Little, Inc., it was estimated that the U.S. tire industry would respond to the growing demand for radial tires such that it could be expected that by 1977, 75% of the new cars produced in the United States would use radial tires, and that these tires would have a 60% or greater life than the belted bias tire presently being used.

TABLE 4-26

SUMMARY EFFECT OF RADIAL TIRES

	Fuel Economy Improvement In %		
	FDC	50 mph	70 mph
CoX Compact	1.83%	1.7 %	0.6 %
CoX Standard	1.38	2.7	2.7
CoX Standard A/C	1.25	2.9	2.9
CoY Compact	2.70	3.7	3.94
CoY Standard	2.12	2.96	4.28
CoY Standard A/C	2.08	4.20	4.44

Summary: Average Savings of 1.8% in FDC
3.1% at 50 mph
2.5% at 70 mph

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[56] Outlook for the U.S. Tire Industry, Arthur D. Little, Inc., Cambridge, Mass., 1973.

Another advantage of the radial tire concept is longer tire life – 50-100% longer, depending on driving conditions. The tire also presents more reliability due to its steel belting. However, not all radial tires have steel belts; the reliability of radial tires without steel belts would probably be similar to bias construction tires. Some bias construction tires also have steel belts. Furthermore, in most cases the handling characteristics of the car using these tires have been improved. We estimate that the cost to the first owner would be between $70-$100 over the present 1973 prices.

4.3.7. Aerodynamics and Fuel Economy

Much research into the effects of aerodynamics on automobile performance has been done with the intent of enhancing the performance of high-speed racing vehicles. However, many of the conclusions drawn from research on sportscar design are directly applicable to contemporary work on American automobile design being conducted to reduce fuel consumption. In the design of high-performance racing cars, aerodynamics is considered primarily for two important effects: (1) the aerodynamic drag, which is the major force limiting the top speed of the vehicle; and (2) the lift upon the vehicle. A poorly designed automobile may experience a positive lift at high speeds which would tend to reduce its handling capability and safety. Both of these factors – aerodynamic drag and lift – are very important not only in the design of high-speed vehicles, but also in improving the fuel economy of conventional passenger vehicles.

Designers of high-performance racing cars are well aware that relatively small changes in body shape may provide as much as a 15% improvement in the drag coefficient which, in turn, could result in a 5% savings in power or fuel consumption at 70 mph, and as much as a 12% savings at race car speeds of 150 mph. The same improvements in vehicle design can provide savings in fuel economy at average speeds.

In addition to the drag and lift force attributable to the aerodynamic styling of a vehicle, the vehicle design also affects other secondary dynamic forces. Aerodynamic styling can affect the lateral force and the pitching, yaw, and rolling moments (see Figure 4-35). The characteristics of these added dynamic forces on the vehicle have been considered in a variety of studies. However, Bowman[57] has shown that the lateral force and accompanying moment coefficients are nearly independent of the body shape and size and depend primarily on the yaw angle, or the angle at which the wind strikes the vehicle. While the magnitude of the forces due to the lateral and moment coefficients do depend on the size and shape of the vehicle, the type of design alterations which would be necessary to affect any of these dynamic forces would be beyond the scope of this study. This is particularly so because these ancillary forces do not directly affect the fuel consumption of the vehicle, even at high speeds, when the aerodynamics has the most pronounced effect on the vehicle. (see Figure 4-36). The insensitivity of the ancillary forces to the shape of the vehicle, plus their small effect on the fuel consumption, precludes them from further consideration.

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[57] Bowman, N., Generalizations on the Aerodynamic Characteristics of Sedan-Type Automobile Bodies, SAE 660389.

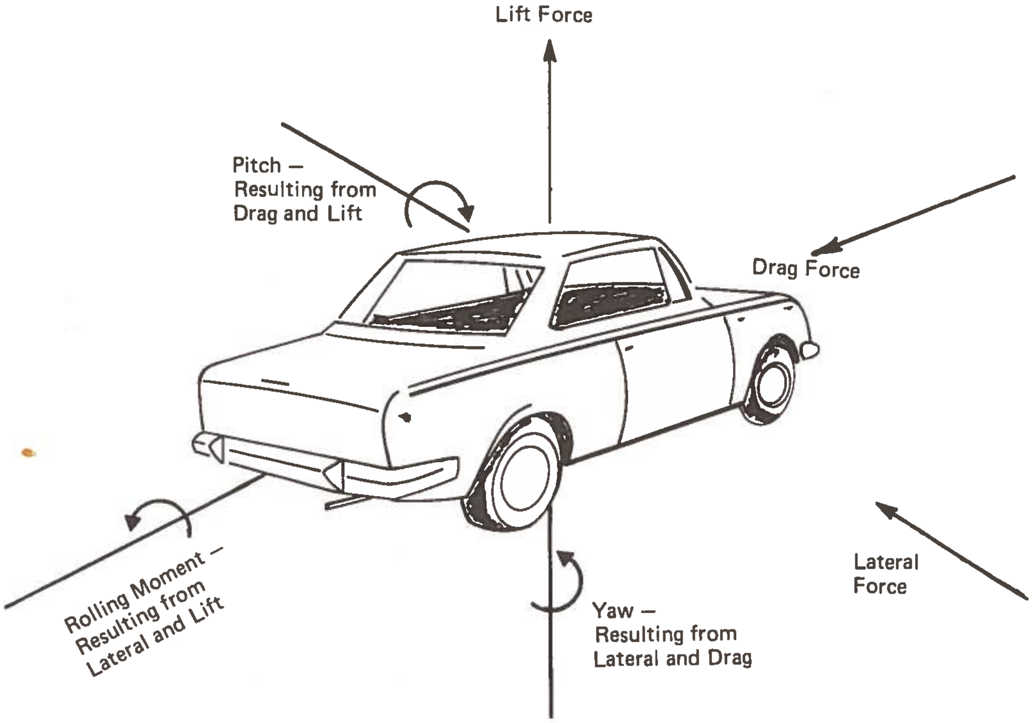

FIGURE 4–35 AERODYNAMIC FORCES ACTING ON MOVING VEHICLE

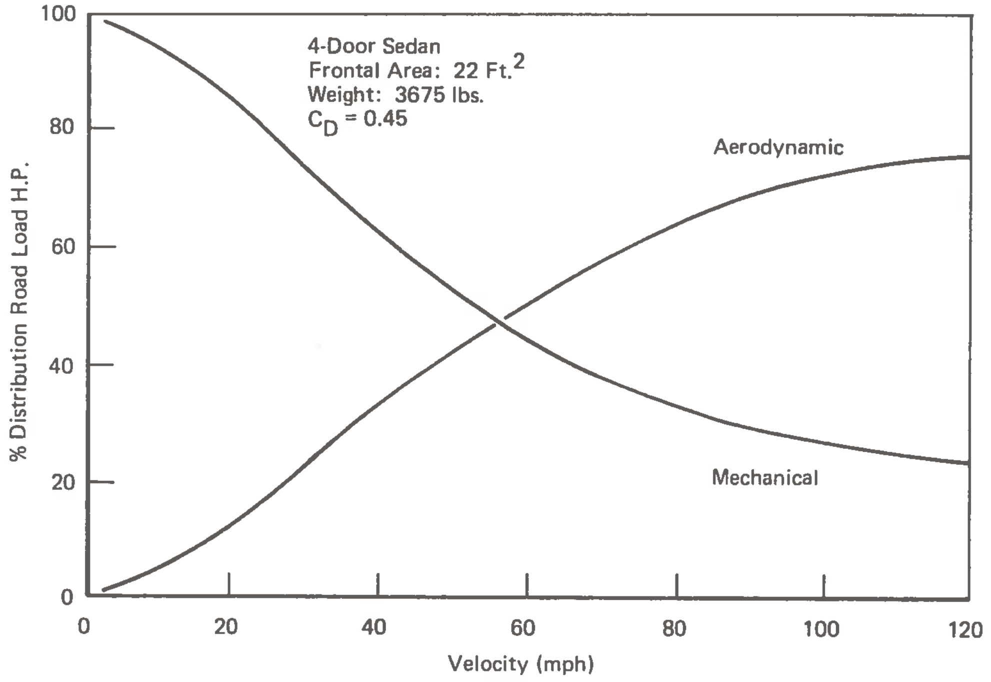

FIGURE 4–36 ROAD LOAD HORSEPOWER DEMAND AS A FUNCTION OF SPEED

Of the various dynamic forces resulting from aerodynamic styling, the aerodynamic drag represents the greatest drain on the power used to propel the vehicle. The aerodynamic drag which acts directly against the motion of the vehicle is a combination of air friction on the exterior of the vehicle and the pressure created as the vehicle in motion pushes air aside.

The drag coefficient $C_D$is a constant and is expressed as the drag force divided by the vehicle frontal area times the vehicle velocity squared times the air density over 2, or

$$C_D = \frac{(14.87) \quad \text{Drag Force}}{\text{Vehicle Frontal Area x (Vehicle Velocity)}^2 \text{ x } \dfrac{\text{Air Density}}{2}}$$

where

Drag Coefficiency – Dimensionless
Drag Force – in lbs-force
Vehicle Frontal Area – in square feet
Vehicle Velocity – in m.p.h.
Air Density – in lbs per cu. ft.

As the formula shows, the drag force exerted on a car is proportional to the drag coefficient times the velocity of the vehicle squared. As Figure 4-36 shows, the percent of horsepower expended due to aerodynamic resistance increases sharply with the speed. The effect on fuel consumption from an improvement in the drag coefficient is therefore very sensitive to the vehicle speed which must be taken into account when assessing potential improvement in fuel economy from aerodynamic styling (discussed later).

The average vehicle considered in this study had a drag coefficient between 0.45 and 0.5. To understand the implications of the drag coefficient/shape relationship, various shapes and their accompanying drag coefficients are presented in Figure 4-37.[58] The optimum shape is a body of revolution with a length about 2.5 times its diameter. This shape has a drag coefficient of 0.04, nearly 0.1 that of the conventional vehicle. The addition of wheels to the optimum aerodynamic shape and other alterations of the vehicle design are also shown. With conventional vehicle design, the minimum drag coefficient of a vehicle would appear to be about 0.2-0.3. This is because the effects of drag due to the wheels and the movement of air in the clearance between the vehicle underpan and the road limit the effect of the vehicle design on reduction of aerodynamic drag.

4.3.7.1. Drag Coefficients and Horsepower Demand

While attempts have been made to correlate the improvement in the drag coefficient with the effect on fuel economy of a vehicle at highway speeds, there is a basic flaw in such a correlation, that is, the force opposing the motion of the vehicle is dependent on the square of the vehicle speed and the drag coefficient product and thus no simple correlation exists between fuel economy and drag. A small change in the drag coefficient for a vehicle moving at 70 mph has a much greater effect on fuel economy than it would on a vehicle moving at 30 mph. Since the yearly usage of the vehicle comprises a mixture of low- and high-speed driving conditions, the direct effect of improving the drag coefficient on the year-end fuel consumption of a vehicle is a fairly difficult relationship to develop. However, some simple relations between the reduction in drag coefficient and improvement in fuel economy can be developed in order to better understand the effect of aerodynamic styling on the fuel economy of vehicles.

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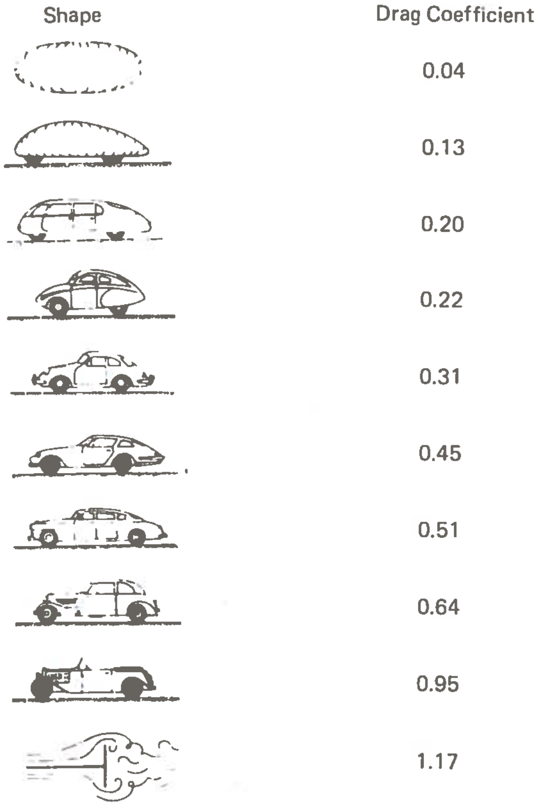
[58] Cornish, J., Some Considerations of Automobile Lift and Drag SAE 650135.



Source: Ref. 58.

FIGURE 4–37 DRAG COEFFICIENTS OF VARIOUS SHAPES

In general, the horsepower necessary to drive a car at a constant speed is the sum of mechanical and aerodynamic resistances. That is:

$$H.P.)_v{}^* = Mech)_v + Aero)_v$$

where

$$Mech)_v = \text{Mechanical Resistance Force x V}$$
$$Aero)_v = C_D\ A\ \frac{\rho V^3}{2}$$

where

ρ = density of air
V = velocity of vehicle
A = frontal area

For most cases considered in the study:

$$Mech = 55\ (\text{lbs})\ \text{x}\ V.$$

If the drag coefficient changes by an amount ΔC_D, then the overall change in horsepower load is:

$$\%\ D\ H.P. = \frac{\%\Delta C_D}{1+\dfrac{Mech.}{\frac{1}{2}\rho V^3 A}} = \frac{\%\Delta C_D}{1+\dfrac{55}{\frac{1}{2}\rho V^2 A}\ \dfrac{1}{C_D}}$$

For most of the vehicles considered in this study the frontal area is 22 sq. ft., and therefore Table 4-27 may be developed for an initial C_D of 0.45 which is typical for the vehicles considered in the study.

These relations are based on the road load power consumption alone and do not reflect the added mechanical horsepower losses in the transmission and rear axle which will mean that the C_D will have even a smaller effect on reduction of vehicle horsepower demand. However, it is clear that at 20 mph (average FDC speed) the effect of the drag coefficient is small and one would not expect much savings in fuel consumption by the reduction of drag at the stop-and-go level of driving.

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* Subscript v indicates that the variable is a function of velocity of vehicle alone.

TABLE 4-27

RELATION BETWEEN DRAG COEFFICIENT AND ROAD H.P. CONSUMPTION

Velocity (mph)	% Δ H.P.
20	% $\Delta C_D/6.33$
30	% $\Delta C_D/3.37$
40	% $\Delta C_D/2.33$
50	% $\Delta C_D/1.85$
60	% $\Delta C_D/1.59$
70	% $\Delta C_D/1.43$

4.3.7.2. Methods of Reducing Drag/Styling Changes

The relationship of the drag coefficient and the particular body styling is complex and subtle. Wind tunnel studies of various vehicle designs have been performed for the last 30 years in an attempt to generalize the relationship of various body styles to the resultant overall drag coefficient. At work at the Motor Industry Research Association, R.G.S. White[59] examined literally hundreds of vehicle designs. Wind tunnel testing of 140 different vehicles resulted in a substantial amount of data which permitted White to develop a drag rating method which may be used to estimate the overall drag coefficient.

The drag rating method essentially divides the vehicle into six basic zones and prescribes a rating number to the particular outline of the vehicle in that zone of the car. The zones include the front, the windshield, the roof, the rear roof, the lower rear end, and the underbody. In each of these zones, White provided a diagram of the various types of vehicle outlines to which the vehicle in question may be compared. For each of the outlines in the zone a drag rating number is assigned. The lower drag rating numbers are assigned to the aerodynamically smooth profiles, while the higher drag rating numbers correspond more to flat-plate, high drag coefficient-type shapes.

In Figure 4-38, three zones of the reference vehicle shapes are shown. The existing vehicle design shows a square front for the plan view of the front, a medium sloped front for the elevation view, and a short rear end for the rear view. These three zones contribute most to the drag rating numbers assigned to the reference vehicles. Three other zones also exist; however, their drag rating numbers are fairly low and it is unlikely that they can be reduced any further. For each of the existing zones an improvement in the body styling is shown, along with the accompanying reduction in the drag coefficient. In each case, the initial drag coefficient is assumed to be 0.43 which is very representative of the reference vehicles. Figure 4-36 shows the reduction of the drag

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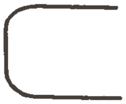
[59] White, R.G.S., A Method of Estimating Automobile Drag Coefficients, SAE 690189, January 1969.

EXISTING	IMPROVED	SAVINGS
 Square Front Drag Rating (DR) = 28 $C_D = 0.43$	 Well Rounded DR = 24 $C_D = 0.38$	11.8%
 Medium Front Slope DR = 28 $C_D = 0.43$	 Low Squared DR = 26 $C_D = 0.407$	4.5%
 Trunk Regular Trunk DR = 28 $C_D = 0.43$	 Short Trunk DR = 26 $C_D = 0.407$	4.5%

Composite of Above Three Configurations

DR = 28 $C_D = 0.43$	DR = 20 $C_D = 0.350$	

$$\therefore \% \text{ Savings} = \frac{.43 - .350}{.43} = 18.6\%$$

FIGURE 4–38 DRAG RATING METHOD FOR REFERENCE VEHICLES

coefficient is very substantial for a change from a square front plan view to a well rounded front plan view. Because of the relationship of the zones the net savings cannot be added directly. However, using the drag rating method, the composite effect of the three zone changes is to reduce the overall drag coefficient by approximately 18%.

White states that his method of evaluation has a ±7% error. This is a substantial error. To assess the practicality of such estimates, we have compared (Table 4-27a) the reduction percentages predicted by White's drag rating method (DRM) with other results.

TABLE 4-27a

COMPARISON OF DRAG RATING METHOD* PREDICTIONS WITH THOSE OF OTHER SOURCES

	% Reduction in C_D			
Change	**DRM**	**Lay[60]**	**Hertz[61]**	**Fossberg[62]**
Front end (plan)	11.6%	18.8%	17.0%	–
Front end (Elevation)	4.5%	–	–	≈5%
Rear end (Ele)	4.5%	6.9%	–	–

*Ref. 59 The data from other studies suggest that the reduction potential for the reference vehicle predicted by White's DRM is within reasonable agreement.

More extensive design changes whose effect on the drag coefficient is quite pronounced are given below.

Change	$\Delta C_D\%$
Raise ground clearance 3 inches	14
Smooth underbody (1/3 length)	11
Close windows and vents	11.4
Close radiator	5
Remove door handles, and number plate, fair rain gutters, and flush lights	9

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[60] Lay, W.E., Is 50 miles per Gallon Possible with Correct Streamlining?, SAE, April 1933.

[61] Hertz and Ukrainetz, Auto-aerodynamic Drag-Force Analysis, Experimental Mechanics, March 1967.

[62] Fossberg, White, and Carr, A British Automotive Wind Tunnel Installation and its Application, SAE 650001.

4.3.7.3. Improvement in Fuel Economy Due to Reduction in Aerodynamic Drag

Based on the effect of design changes on the three zones discussed earlier, we believe that a 20% improvement in drag coefficient can be achieved by incorporating simple styling changes in the vehicle design. As mentioned earlier, rounding of the front end may reduce the drag coefficient by 12% alone; raising the ground clearance may also decrease the drag coefficient; however, stability of the vehicle becomes a problem. Other design changes, such as smoothing the underbody, and removal of door handles, and number plates, fairing in the rain gutter and lights, may also – in composite – reduce the drag coefficient by about 10%. These design changes therefore may provide the 20% reduction in drag coefficient.

The resulting effect of a 20% reduction in drag coefficient has been assessed by exercising the computer program over the federal driving cycle and examining the effect of a 20% reduction in drag coefficient for the FDC and at steady speeds. The summary of the effect of the 20% reduction in drag is shown in Table 4-28. The table shows that the drag coefficient reduction does not substantially improve the mileage of the vehicle for the federal driving cycle for which the vehicle has an average speed of about 20 mph. Earlier we stated, that at low speeds, such as 20 mph, the predicted percent fuel improvement effected by reducing the horsepower necessary to propel the vehicle due to road load requirements alone is substantially less than at higher speeds. Since horsepower demand and fuel consumption are directly related, the effect of aerodynamic styling is expected to be less pronounced at lower speeds. Thus, the growing improvement in miles per gallon for the 10% reduction in drag coefficient as the average speed is increased from federal driving cycle to 50 and 70 mph steady speeds is reasonable.

TABLE 4-28

SUMMARY EFFECT ON A 20% REDUCTION IN AERODYNAMIC DRAG ON REFERENCE VEHICLES

Reference Vehicle	Improved MPG in Percent for FDC	50 mph	70 mph
Co X Compact	0.86	2.5	3.9
Co X Standard	0.68	2.2	3.4
Co X Standard with Air Conditioning	0.44	2.3	3.6
Co Y Compact	0.95	3.2	6.0
Co Y Standard	0.63	1.5	3.8
Co Y Standard with Air Conditioning	0.52	2.4	4.1

Summary: Average savings of 0.70% in FDC, 2.5% at 50 mph, and 3.8% at 70 mph.

The average savings of about 0.7% in the federal driving cycle and 2.5% at 50 mph and 3.8% at 70 mph, though not a substantial reduction in the fuel consumption of the vehicle, still represent gains for what may be considered minor costs. This is particularly so if changes are incorporated at major body styling changes. For the purpose of this study we have planned that changes will be incorporated at major body changes and therefore no incremental cost will be charged to the first owner.

4.3.8. Vehicle Weight Reduction

4.3.8.1. Introduction

Vehicle weight is an important parameter affecting fuel economy. Weight contributes to increased vehicle fuel consumption in three ways: 1) by increased rolling resistance to overcome tire flexing losses and bearing friction losses, 2) through the increased energy required to drive the vehicle up grades, and 3) by increasing the power required to accelerate the greater vehicle mass. These factors all increase in direct proportion to vehicle weight. However, fuel consumption is not directly proportional to vehicle weight, because a substantial portion of the power required to propel the vehicle results from aerodynamic drag which is not directly a function of weight. However, indirect effect may result if the weight increase necessitates an increase in vehicle size in such a manner that the aerodynamic drag is increased as well.

The variation in average miles per gallon over the Federal Driving Cycle (FDC) with vehicle inertia weight as determined by EPA for a large population of 1973 and earlier model cars is shown in Figure 4-39 generated from References 63 and 64 as a source. Similar data obtained by Ford on a large population of cars driven over their city-suburban route are also summarized by the dashed curve shown on Figure 4-39 according to a formula presented by LaPointe.[56] Relatively good agreement is shown between these two sources. Although these data represent the average results from a large number of different cars of different sizes and characteristics, the vehicle weight appeared to be the most important parameter against which to plot the data for correlation purposes. The effects of engine size, power accessories, aerodynamic characteristics, transmission differences, acceleration capability, axle ratio, tires, and the like, are also included in the data summarized in Figure 4-39. However, the predominant effect shown is due to vehicle weight.

It is appropriate to observe, however, that the slope of the curve (as measured in % mpg increase/% weight decrease) increases with decreasing weight due, not doubt, to the fact that the smaller cars frequently have lower power-to-weight ratios (poorer acceleration) and fewer power-consuming accessories such as power steering, air conditioning, etc.

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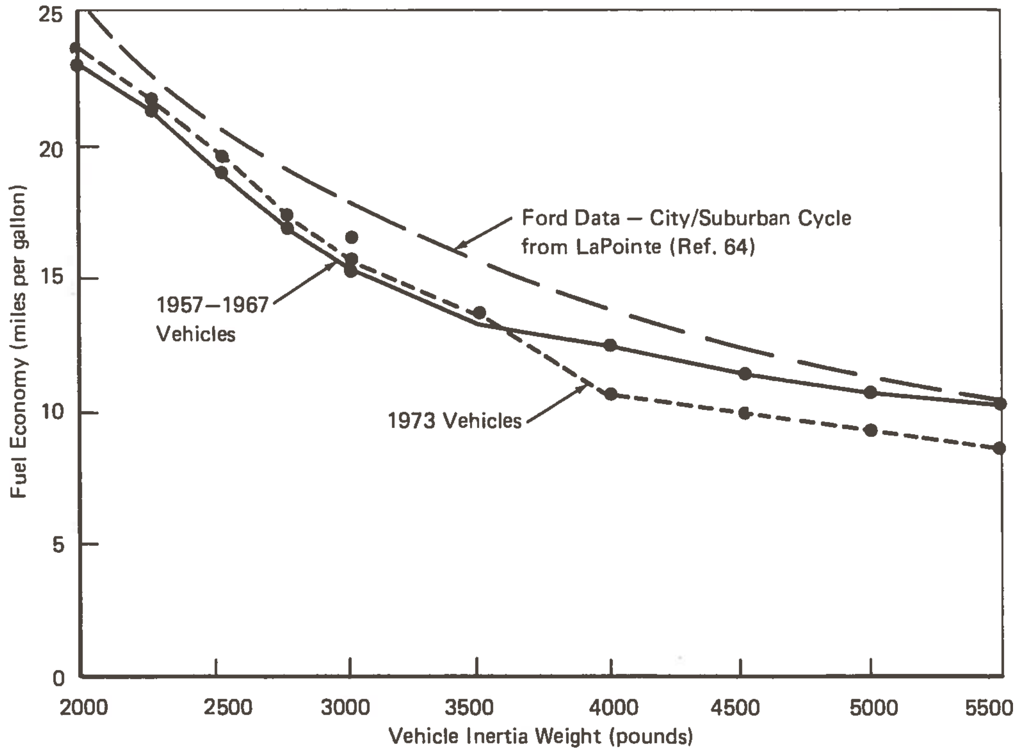
63. Anon. Automotive Fuel Economy, U.S. Environmental Protection Agency, Mobile Power Source Pollution Control Program Publication, October 1973.
64. LaPointe, C., Factors Affecting Vehicle Fuel Economy, SAE Paper No. 730791, Milwaukee, Wisconsin Meeting, September 11, 1973.



Source: Ref. 63.

FIGURE 4–39 FUEL ECONOMY VERSUS INERTIAL WEIGHT FOR UNCONTROLLED (1957–1967 AVERAGE) AND 1973 VEHICLES

Having established that fuel economy is strongly dependent on vehicle weight, appropriately enough we examined the recent trend in automobile weights within a given vehicle class. One manufacturer recently reported the following figures for the weight growth of a typical middle-sized car from 1966 to 1976:

Year	Car Weight	% Increase
1966	3,670	–
1972	3,900	6%
1976	4,500	12.3%

The '66-'72 weight increases may be attributed almost equally to three separate factors:

1) Functional requirements (engines, suspensions, climate control and exhaust systems),

2) Product content (body size, glass area, air conditioning, power seats, sun roofs),

3) New federal requirements for safety, emissions, damageability, and noise.

In contrast, the expected weight growth from 1972 to 1976 is due almost entirely to safety, emissions, damageability and noise requirements.

With fuel economy becoming far more important than in recent years, it is imperative that weight reduction be considered high on the list of alternatives for vehicle improvement.

4.3.8.2. Computer Simulation Results on Effect of Weight Reduction

Computer simulation runs were made to investigate the effect of weight reduction alone (with all other vehicle parameters remaining unchanged) and to examine simultaneous reductions in weight and axle ratio to preserve nearly constant acceleration performance.

After establishing that the effect of weight reduction is indeed linear (% fuel saving ÷ % weight reduction = constant), a 10% weight reduction was assumed for each of the four reference vehicles examined. Detailed results are contained in the appendix (SES report). Table 4-29 shows the results expressed as percent improvement in mpg for operation over the Federal Driving Cycle (FDC) and for steady level-road driving at 50 and 70 mph. Excellent agreement is obtained among the six simulation runs shown. The fuel economy improvement is about 4% over the FDC and about 2.5% at 50-70 mph steady speed. The lower improvement during high-speed driving results from the greater influence of aerodynamic drag on vehicle power demand at high speeds. These simulation results agree well with industry findings as reported by LaPointe,[64] Huebner,[65] and Austin and Hellman[66] (Table 4-29).

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[65] Huebner, G.J., Jr., and Gasser, D.J., General Factors Affecting Vehicle Fuel Consumption, SAE Publication SP 383, from National Automobile Engineering Meeting, Detroit, Michigan, May 1973.

[66] Austin, C., and Hellman, K., Passenger Car Fuel Economy Trends and Influencing Factors, SAE Paper 73090, Sept. 10-13, 1973.

TABLE 4-29

EFFECT OF 10% WEIGHT REDUCTION AND COMBINED WEIGHT AND AXLE RATIO REDUCTION ON VEHICLE FUEL ECONOMY

Data Source	Weight Reduced by 10% % Improvements in MPG			Combined Weight and Axle Reduction by 10% % Improvements in MPG		
	Federal Urban Driving Cycle	50-MPH Steady State	70-MPH Steady State	Federal Urban Driving Cycle	50-MPH Steady State	70-MPH Steady State
Computer Simulation Runs:						
Co. X Compact	4.01	2.1	1.7	–	–	–
Co. X Std. A/C* off	3.70	2.2	1.4	–	–	–
Co. X Std. A/C on	3.58	2.3	2.2	–	–	–
Co. Y Compact	4.6	2.42	2.45	6.0	3.5	6.0
Co. Y Std. A/C off	3.56	2.15	2.78	–	–	–
Co. Y Std. A/C on	3.42	2.80	2.48	5.5	8.0	5.5
Data From Tech Literature:						
LaPointe (Ref. 64)	3.0	–	–	6.5	–	–
Huebner (Ref. 65)	4.3	–	2.5	–	–	–
Austin & Hellman (Ref. 66)	4.1-4.6	–	–	–	–	–

*Air conditioning

If the vehicle weight is reduced while all other design parameters remain unchanged, an improvement in acceleration performance will result. Huebner[57] states that a 10% acceleration improvement will accompany a 10% weight reduction. Therefore, it seems reasonable to project a reduction in axle ratio and/or engine displacement, along with the 10% weight reduction, to hold a constant acceleration performance. This was done on some simulation runs with the Company Y cars by simultaneous reductions in weight and axle ratio. Those results are also presented in Table 4-29 under the column labelled "Combined weight and axle reduction by 10%." Again these results agree well with those of LaPointe[56] and show about 6% economy improvement under all conditions for the 10% weight and axle reduction.

4.3.8.3. Methods of Achieving Weight Reduction

Before considering how weight reduction could be achieved, it would be of interest to review how various materials contribute to the weight of automobiles. Table 4-30 shows a weight breakdown of a standard size car by materials of construction. Steel accounts for over one-half of the total weight, while cast iron is next with 650 pounds of the 4000-pound total. Rubber and fluids both account for about 200 pounds, while aluminum, glass, plastics, soft trim, and so forth, account for about 100 pounds each.

TABLE 4-30

WEIGHT BREAKDOWN OF STANDARD SIZE CAR BY MATERIALS OF CONSTRUCTION

Plymouth Fury III – V-8 engine, power steering, power brakes, auto-transmission, and radio

Total weight 4,014 lb

Constituents	Wt. (lb)
Carbon steel	2,105
Galvanized steel	75
Aluminized steel	31
Alloy steel	95
Stainless steel	13
Total steel	2,319
Cast iron	651
Aluminum	75
Fluids and lubricants	216
Rubber	201
Glass	96
Plastics	125
Soft trim, composition, etc.	110
Paint	26
Sound deadening	77
Lead & body solder	27
Zinc	65
Copper	26

There are three basic methods of reducing weight: 1) reducing vehicle size, 2) careful engineering and redesign on a "systems engineering" basis to eliminate non-essential weight, and 3) substitution of lighter materials. The first method is an obvious approach and requires no further discussion.

4.3.8.3.1. Engineering for Reduced Weight – Whenever the weight of a given part is reduced, there is usually an opportunity to reduce structural weight elsewhere as a result of the initial weight-saving. Components such as the frame, support members, body structure, tires, brakes, steering, etc., can be reduced when a significant weight-saving is made elsewhere. A typical average estimate for this weight compounding factor is 0.5 pound of structural weight for each pound of component weight saved. This technique of "engineering for weight" in which the interrelationship of all components is examined is known as systems engineering. It will have to be practiced more extensively if substantial quantities of weight are to be removed from automobiles without sacrificing the functions intended for all its parts.

In the initial rush to meet new government standards for safety, damageability, and emissions, the solutions implemented to date probably do not represent the best ultimate alternatives for lowest weight and cost. Better solutions with lower weight penalties are likely to ensue as the designs can be integrated with styling changes and model changes.

Perhaps one of the most promising methods of reducing weight is to redesign certain structural parts using alternate materials with a higher strength/weight ratio. One of the principal developments that is receiving considerable attention is the new high-strength/low-alloy (HSLA) steel. Some of these materials offer a two- to three-fold increase in yield strength, while suffering a one-third reduction in formability. There is some controversy over the formability and welding characteristics of these HSLA steels as compared with low-carbon steel.[67] While some claim that the formability and welding characteristics are inferior, others claim they are equal to carbon steel. Until these characteristics are resolved, the industry will undoubtedly move slowly in implementing these new steels.

Some of the potential automotive applications for HSLA steels have already been converted, but large-scale uses in such items as frames, suspension parts, wheels, body structure and panels are yet to come. Typically the HSLA steels will allow a material gage reduction of about two gage sizes in structural members. Since about 60% of a typical automobile consists of sheet steel, this material offers considerable potential for weight reduction. Corrosion-resistance of HSLA steels is claimed to be from 2-8 times better than that of carbon steels, but the reduced gage thickness could present problems in critical corrosion areas.

Because the industry has been cautious and slow to apply the newer steels, a backlog of attractive new steel products (e.g., textured and coated sheet, hot-rolled weathering steels, improved galvanized steels, etc.) has developed that will be competing with other possible material substitutes for the auto designers' attention. The ability of steel to meet so many requirements, while offering superior energy-absorption characteristics over a wide temperature range suggests its probable continued use for most automotive applications. Moreover, its capability for rapid forming and finishing, ease of fastening and joining, resistance to heat, ease of repair, adaptability to recycling and, of course, its low cost continue to make steel the industry's choice for most automotive uses.

Potential weight savings with HSLA steels is uncertain, but some parts can realize up to 50% weight reduction. It seems reasonable, therefore, to expect a possible saving of 300-400 pounds by use of these materials.

4.3.8.3.2. Material Substitution – There is considerable potential for reducing weight through redesign, making use of alternate materials which offer weight-saving potential. Aluminum and plastics are two candidates which deserve attention.

4.3.8.3.2.1. Aluminum – Aluminum is a plentiful material which offers considerable potential for reduced weight in automobiles. Currently it is used for transmission housings and parts, engine pistons, alternator housings, air conditioning equipment, trim, and more recently for some bumpers and structural parts. Alcoa[68] has studied many other uses and has recently suggested the following additional applications for aluminum in automobiles: radiators, heater cores, hoods, rear decks, doors, tailgates, bumpers, interior seat frames, floors, wheels, air and oil cleaners, fan blades, shrouds, and energy-absorbing devices. Although all of these applications would allow weight reductions, cost will be the principal factor governing the material selection. Alcoa claims a 300-pound weight reduction can be achieved by the use of aluminum substitutions for four body parts as follows:

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[67] Pond, J.B., Eshelman, R.H., and Gottesman, C.A., Materials: New Marriages in Design, Automotive Industries, December 15, 1973.

[68] Alcoa, The Automobile and Aluminum, 1973.

Component	Weight (lb)	
	Aluminum	Steel
Hood	35	90
Trunk lid	30	75
Doors (4)	100	250
Bumper reinforcements	35	90
Total	200	505

Weight Savings = 305 pounds

Alcoa's analysis shows a $32.40 cost premium for the aluminum material over its steel counterpart (including an allowance for aluminum scrap value), which diminishes to $15.70 if a credit is taken for a possible 152-pound reduction in steel structure made possible by the reduced weight of the aluminum components. Alcoa estimates that the total weight reduction of 457 pounds would allow a 500-gallon savings in fuel over 100,000 miles of vehicle operation. At $0.50/gallon this represents a $250 savings in fuel cost. In spite of this apparent life-cycle cost benefit, the first cost is greater, and there is a reluctance on the part of auto manufacturers to adopt any weight-saving changes that increase the product cost. This attitude should begin to change as the customer becomes more concerned about fuel usage and begins to shop around for a more efficient vehicle.

There are certain production problems and service/repair problems involved in the use of aluminum exterior panels. Dents in aluminum are not so easily repaired as steel dents, but epoxy fill repair techniques and a variety of adhesives for production uses may prove practical. Some production experience with aluminum body panels is expected to be initiated soon.

Questions frequently raised regarding the extensive use of aluminum in automobiles generally concern the impact on aluminum production capacity, mineral reserves, and energy requirements. These questions are also dealt with in Reference 60. Increasing aluminum usage to 200 lb/car from a baseline figure of 81 lb/car would require an increase in industry capacity of about 15%. The impact on Free World bauxite reserves does not appear critical, but much of this resource would have to be imported. Alcoa[60] claims that the energy required to produce an equivalent aluminum part is about equal to, or (if recycling is considered) less than its counterpart – steel.

In summary, it appears that increased use of aluminum can result in significant weight savings (about 10%), but it is not clear whether its use would compete economically with steel, or whether manufacturers and users would begin to consider life-cycle cost effects rather than making decisions based solely on the first cost.

4.3.8.3.2.2. **Plastics** – Plastics represent another material substitution possibility for achieving weight reduction. There has been a dramatic increase in the use of plastics in automobiles in recent years, particularly polypropylene for interiors. In addition, some functional parts, such as housings, fan blades, gears, bushings, etc., have been injection-moulded from nylon, Delrin^{TM}, etc. Such uses will continue to grow, unless they are curtailed by the current short supply problem or by significantly higher prices for feedstock material. Most of the plastic functional parts enjoy a 50% weight reduction over equivalent parts from zinc die catings, steel stampings, etc.

The newest area where plastics are used is in the entire front-end where soft elastomeric materials are used as masks. A second generation of energy management systems may utilize an energy-absorbing unit under a soft plastic facia panel which flexes with impact. If one of the several systems currently under development should attain widespread use, it would have a substantial impact on the increased use of plastics in automobiles.

Fiber glass-reinforced plastic may be considered as a substitute for steel for some structural members and in some cases can result in weight savings. However, it is not expected to see widespread use in auto bodies because (1) the moulding cycle time is about 4-5 times the press time for a steel part, thus increasing production cost for large volumes, and (2) the reinforced plastic parts do not possess the desirable energy-absorbing characteristics and resistance to low temperatures comparable in steel parts.

4.3.8.4. Summary

Based on the discussion above, it is reasonable to expect to achieve a 10% weight reduction by implementing these techniques. Therefore, a 10% reduction was used in the vehicle simulation studies to examine the fuel economy impact of weight reduction. It was also assumed that an increase in vehicle cost would accompany this weight reduction. The additional cost was estimated to be $100 for the standard car and $80 for the compact car.

The vehicle changes required for a major weight reduction would necessarily be introduced during major model design changes which only occur at three- or four-year intervals. Two or more model changes may be required to realize the full 10% weight reduction. The auto manufacturers are already working on many of these approaches to weight reduction and some progress can be expected by the 1977 and 1978 model years. A full 10% reduction is likely by the 1980 model year.

During the course of this study we interviewed those in the industry who were experienced and knowledgeable regarding the length of time required to effect a major body and chassis change. We found that the industry plans on taking approximately four years to produce a brand new car and attempts made to reduce this time have been unsuccessful and have been accompanied with high risks in terms of costs and call-backs of cars delivered to customers.

In a recent article[69] appearing in the Automotive Industries, it was pointed out that studies conducted by Frank Walter of Chrysler Corporation over the past two decades indicate there has been about a 10-week reduction in the 140- to 144-week gestation period of a new car after program approval. This amounts to a mere 7% reduction.

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[69] Callahan, J.M., Shortening Lead Time Equals Increased Risks, Automotive Industries, July 15, 1973

We also feel that not all the improvements related to the reduction of weight, aerodynamic drag, and frontal area could be realized in the first major change – more like one-half of the gain. The remaining improvements would be accomplished with the next major change.

4.3.9. Miscellaneous Innovative Devices for Improving Fuel Economy

In addition to the individual improvements which have been described, there are a number of miscellaneous innovative devices which the automotive manufacturers and innovators are examining and, in some cases, will be offering as retrofit, or as original equipment on all models of future cars. The items below show the wide scope of devices being considered, but we have not attempted to evaluate them since we were unable to obtain sufficient data about them, or because time did not permit a thorough study. It is interesting to note that many of these concepts are not new. In fact, they are based on approaches that have existed for some time, but apparently offered only slight improvement and, where possible, were not fuel/cost-effective. The concepts include:

1. Carburetor Degassers – A carburetor degasser is used to shut off the fuel supply when a high manifold vacuum is present during decelerating periods. It is controlled automatically by the manifold vacuum, but also can be made with an electric solenoid to shut off the fuel supply positively after the ignition is cut. This device was used for tank engines and incorporated in the Stromberg carburetor Model NA-Y5G.[70]

   It appears to be relatively uncomplicated and effective. A very rough estimate of deceleration from the rationale developed in Section 4.1.2 indicates that approximately 5-10 gal/yr could be saved using this device. Absolutely no attempt has been made to consider how this device would affect emissions or customer acceptance.

2. Mileage Meters – A number of devices will be introduced in the near future which the motorist may purchase for retrofit on existing cars or be included on new cars. They range from warning lights and simple vacuum gauges (a device which has been available to the motorist for years) with needles pointing to a red area (poor mileage) or a yellow and green area (good mileage), to sophisticated calibrated indicators that display the miles per gallon based on fuel flow to the carburetor versus rate of speed.[71] The devices are undoubtedly useful if the motorist knows how to use them and if, in fact, he acts on the information.*

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70. U.S. Army Repair Manual, TM-9-1826B.

71. Raphael, S., Cox Mileage Meter-Gimmick or Gas Saver, Ward's Auto World, January 1974.

* In Chapter III (Section 3.3.1.2., Figure 3-1) we showed that as much as a mile per gallon could be saved or lost based on driver habits.

3. Reduced Mechanical Friction of the Engine – We hesitate to broach the subject of potential savings through reduced mechanical friction of the engine – either through improved lubricants or by redesign of components – because of the years of concentrated research and development that has been applied to these areas. This is particularly so when one considers the small possible incremental savings versus the potential loss in reliability, maintainability, and durability that might occur if a change is not thoroughly proven out.

   However, effort is continually being expended in this area. For example, the Climax Molybdenum Company of Michigan has worked for years on developing molybdenum disulfide as an oil additive to reduce engine friction, and it claims an approximate 2% improvement in fuel economy if used properly.[*,72]

   Automotive Engineering Research, Madison, New Jersey[73] has been working some years on the development of a single-ring piston design incorporating the balancing of the partial vacuum between the combustion chamber and crankcase during the intake stroke which has been described as possibly reducing ring and piston friction without a commensurate increase in blow-by and oil consumption, and without compromising durability and reliability.

   We are sure that these two areas are only indications of work being done to reduce fuel consumption caused by engine friction, even though only marginal improvements are possible.

4. Variable Displacement Spark Ignition Engines – At the start of this project we reported on our consideration of a variable displacement engine which would, in effect, accomplish the goal of more fully loading an engine during moderate cruise conditions, but provide the displacement for W.O.T. conditions if required. We did not proceed further with this approach because of the lack of usable data to perform an evaluation. However, recently it appears that the Pontiac Motor Division of General Motors[74] is examining the possibility of a concept that uses a conventional V-8 engine operating essentially as a dual displacement engine.

   We think that this approach should be investigated to the point that its cost effectiveness is proven.

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[72] Wahrenbrak, M., The Effect of Molybdenum Disulfide in the Crankcase Oil on Engine Performance, Ethyl Corporation Report NO-RS-222, Project 90704-5, February 13, 1963.

[73] A Case for the Single-Ring Piston, Hot Rod Magazine, December 1973.

[74] Callahan, J., Pontiac is Holy Grail – Fuel Economy, Automotive Industries, December 1, 1973.

[*] Letter to D.A. Hurter from H.F. Barry, Manager of Chemical Research, Climax Molybdenum Company of America, January 10, 1973.

4.3.10. Summary Evaluation of Individual Improvements

4.3.10.1. Introduction

The purpose of this subsection is to show the possible fuel economy improvements or fuel usage reduction for each of the individual improvements and to measure these improvements against the constraints of the project. We have done this by:

- Determining the gallons used by a vehicle equipped with the improvement and driven more than 10,000 miles, using the formula developed in Section 4.1.2.
- Relating the total gallons used to that used by the reference vehicle to determine the gallons saved and the percentage of improvement for each approach.
- Having determined the gallons saved by each improvement, we performed a cost benefit analysis for each and showed the dollar savings possible using various costs of gasoline per gallon, and various discount rates for the money initially invested and for repairs, replacement, and maintenance. We then compared all the improvements against the constraints of the project and against one another to select those best suited for use in the synthesized vehicle.

4.3.10.2. Summary of Fuel Usage Reduction and Fuel Economy Improvement Analysis

By using the information furnished by the developers of innovative devices and manufacturers of the reference vehicles and the computer simulation techniques and rationale for computing tank mileage developed in Section 4.1.2, we were able to estimate the relative differences in fuel consumption or tank mileage for each innovation.

Table 4-31 is a documented example of how this was done using a company X standard size reference vehicle first equipped with bias belted tires for which radial tires were substituted as an improvement.

Similar analyses were made for all the individual improvements and later for the synthesized vehicles, providing sufficient data were available to simulate the operation of the automobile. Appendix V contains the results and conclusions for each of some 180 runs.

For our purposes, Tables 4-32 through 4-35 summarize the essential data obtained from the simulation program and provide the essential fuel saving data for performing a cost-effectiveness evaluation.

In addition to determining the amount of fuel saved through the computer simulation technique, we calculated how much would be saved, on the basis of best estimates available from our interviews and information provided us by the industry. We compared these results from all sources before deciding what conservative percent of reduction could be achieved within the goals and particularly the emission constraints of this program.

TABLE 4-31

EXAMPLE OF TANK MILEAGE CALCULATION AND COMPARISON OF THE SUBSTITUTION OF RADIAL TIRES AS AN INDIVIDUAL IMPROVEMENT ON 1973 STANDARD COMPANY X REFERENCE VEHICLE FURNISHED WITH BIAS BELTED TIRES

Simulation Configuration	Driving Mode	Miles Driven in Mode 10,000 Total Miles Driven in 1 Year	Fuel Economy (mpg) From Computer or Supplied Data	Total Gallons Fuel Used in Specific Mode During 1 Year's Driving
Company X Reference Vehicle Standard Size Bias Belted Tires	Federal Drive Cycle	3,300	11	300
	30 mph steady-state	2,100	19	110.52
	40 mph	1,000	19.8	50.52
	50 mph	1,900	18.6	102.15
	60 mph	1,300	16.5	78.79
	70 mph	400	14.6	27.39
		10,000	14.94 (tank mileage)	669.37
Same Except for Radial Tires	Federal Drive Cycle	3,300	11.15	295.96
	30 mph steady state	2,100	19.4	108.25
	40 mph	1,000	20.3	49.26
	50 mph	1,900	19.1	99.48
	60 mph	1,300	17.0	76.47
	70 mph	400	15.0	26.67
		10,000	15.24 (tank mileage)	656.09

Summary: Using radial tires for standard reference vehicle X in place of bias belted tires as originally furnished results in:

(1) Gallons saved in 10,000 miles – 13.28
(2) % improvement in tank mileage – 2.01%
(3) % reduction in fuel usage – 1.94%

TABLE 4–32 SUMMARY OF FUEL USAGE FOR ANNUAL TANK MILEAGE AND PERCENT IMPROVEMENT FOR COMPANY X COMPACT SIZE VEHICLE (Without Air Conditioning)

Simulation Configuration	Type of Transmission	FDC Fuel Economy MPG	Steady-Speed Fuel Economy (mpg)					Total Gallons Used in 10,000 Miles Based on Tank Mileage Formula	Fuel Economy (mpg)	Fuel Usage (gpm)	% Improvement (mpg)	% Reduction (gpm)
			30	40	50	60	70					
1. Reference Co. X Compact	STD	17.5	27.9	27.1	23.8	20.7	17.8	466.39	21.44	.0466	–	–
2. Radial Tires Substituted	STD	17.8	28.6	28.5	28.0	22.0	18.9	450.48	22.20	.0450	3.54	3.43
3. 10% Less Weight	STD	18.2	28.8	27.6	24.3	21.1	18.1	452.87	22.08	.0453	2.99	2.79
4. 10% Less Frontal Area	STD	17.6	28.3	27.5	24.4	21.4	18.5	458.31	21.82	.0458	1.77	1.72
5. 20% Less Drag	STD	17.7	28.6	27.9	25.0	22.0	19.2	451.63	22.14	.0452	3.26	3.00
6. Including All Add-ons (1-5)	STD	18.9	32.0	30.6	27.5	24.0	21.0	415.21	24.08	.0415	12.3	10.9
7. Reference	CVT	21.1	39.0	40.0	33.7	28.8	21.5	355.37	28.14	0.355	31.3	23.8
8. Reference + Add-on's (6)	CVT	22.7	40.3	47.0	39.0	34.0	27.0	320.53	31.20	.0321	45.5	31.1
9. Diesel 2.79 Axle	STD	21.9	32.1	29.8	26.6	23.2	20.1	399.00	25.062	.0399	16.8	14.3
10. Diesel 3.08 Axle	STD	21.4	30.5	27.8	24.6	21.3	18.4	417.00	23.98	.0417	11.8	10.6
11. Diesel + Add-on's (1–5)	STD	23.6	34.6	32.3	28.3	24.7	21.4	369.94	27.03	.0370	26.1	20.6
12. Diesel + Add-on's (1–5)	4-sp + Lock-up	21.4	40.8	43.6	38.5	32.8	28.2	331.78	30.14	.0332	40.6	28.8
13. Diesel	CVT	25.8	40.0	41.5	38.5	32.3	26.7	309.08	32.35	.0309	50.9	33.7
14. Diesel + Add-on's (1–5)	CVT	27.9	43.4	46.2	44.6	38.2	31.8	277.52	36.03	.0276	68.1	40.8

TABLE 4–33 SUMMARY OF FUEL USAGE FOR ANNUAL TANK MILEAGE AND PERCENT IMPROVEMENT FOR COMPANY X STANDARD SIZE VEHICLE (Without Air Conditioning)

Simulation Configuration	Type of Transmission	FDC Fuel Economy (mpg)	Steady-Speed Fuel Economy (mpg)					Total Gallons Used in 10,000 Miles Based on Tank Mileage Formula	Fuel Economy (mpg)	Fuel Usage (gpm)	% Improvement (mpg)	% Reduction (gpm)
			30	40	50	60	70					
1. Reference Co. X Standard	STD	11.0	19.0	19.8	18.6	16.5	14.6	669.37	14.94	.0669		
2. Radial Tires Substituted	STD	11.1	19.4	20.3	19.1	17.0	15.0	656.09	15.24	.0656	2.01	1.94
3. 10% Less Weight	STD	11.4	19.3	20.1	19.0	16.9	14.8	651.99	15.34	.0652	2.68	2.54
4. 10% Less Frontal Area	STD	11.1	19.1	20.1	19.0	17.0	15.1	661.03	15.13	.0661	1.27	1.20
5. 20% Less Drag	STD	11.2	19.2	20.3	19.4	17.5	15.6	653.26	15.31	.0653	2.48	2.39
6. Including All Add-on's (1–5)	STD	11.7	20.6	22.0	21.6	19.6	17.3	606.86	16.48	.0607	10.31	9.27
7. Reference	STD + Lock-up	11.6	20.0	20.8	19.6	17.5	15.1	635.27	15.74	.0635	5.35	5.08
8. Reference	4-sp	11.0	19.5	20.3	19.0	17.0	15.1	659.91	15.15	.0660	1.41	1.34
9. Reference	4-sp + Lock-up	11.7	20.0	21.0	19.3	17.5	15.1	633.89	15.78	.0634	5.62	5.23
10. Reference → 290 CID	CVT	13.1	20.2	24.9	23.8	17.3	16.3	582.87	17.17	.0583	14.93	12.85
11. Reference + Add-on's (6)	CVT	13.7	23.3	28.3	28.1	25.1	22.1	505.21	19.80	.0505	32.54	24.51
12. Reference + Add-on's (6)	4-sp + Lock-up	12.5	22.8	25.8	23.1	20.2	17.9	564.82	17.70	.0565	18.47	15.6
13. Diesel 400 CID	STD 3-sp	13.5	21.0	20.8	18.8	16.0	14.7	602.05	16.61	.0602	11.18	10.0
14. Diesel + Add-on's (6)	STD 3-sp	14.5	24.8	25.1	23.8	21.4	19.4	513.30	19.48	.0513	30.39	23.3
15. Diesel 2.75 Axle	4-sp + Lock-up	13.7	25.0	28.1	25.3	22.1	19.0	515.83	19.39	.0516	29.79	22.9
16. Diesel	CVT	16.6	26.0	29.3	29.4	25.0	20.4	450.72	22.19	.0451	48.53	32.6
17. Diesel + Add-on's, 350 CID	CVT	17.6	27.7	31.7	33.0	30.9	25.6	410.13	24.38	.0410	63.19	38.7
18. Diesel 2.5 Axle	4-sp + Lock-up	14.1	25.2	29.8	26.5	23.1	19.3	501.31	19.95	.0501	33.53	25.1
19. Diesel 2.5 Axle + Add-on's (6)	4-sp + Lock-up	15.1	28.0	32.0	29.8	26.3	23.0	456.83	21.89	.0457	46.52	31.7
20. Stratified Charge	STD	13.2	24.0	23.5	20.2	18.1	14.9	572.78	17.45	.0572	16.80	14.5

TABLE 4–34 SUMMARY OF FUEL USAGE FOR ANNUAL TANK MILEAGE AND PERCENT IMPROVEMENT FOR COMPANY Y STANDARD SIZE VEHICLE (Without Air Conditioning)

Simulation Configuration	Type of Transmission	FDC Fuel Economy (mpg)	Steady-Speed Fuel Economy (mpg)					Total Gallons Used in 10,000 Miles Based on Tank Mileage Formula	Fuel Economy (mpg)	Fuel Usage (gpm)	% Improvement (mpg)	% Reduction (gpm)
			30	40	50	60	70					
1. Reference Co. Y Standard	STD	10.4	18.6	18.5	17.3	15.4	14.0	707.08	14.14	.0707		
2. Radial Tires Substituted	STD	10.6	19.2	19.3	17.8	16.2	14.6	686.89	14.56	.0687	2.97	2.83
3. 10% Less Weight	STD	10.7	19.1	19.0	17.6	15.9	14.4	688.48	14.52	.0688	2.69	2.68
4. 10% Less Frontal Area	STD	10.4	18.8	18.8	17.5	16.0	14.5	647.29	14.34	.0647	1.41	8.49
5. 20% Less Drag Coefficient	STD	10.5	19.0	19.0	17.8	16.5	15.1	689.46	14.50	.0689	2.55	2.55
6. Including all Add-on's (1-5)	STD	11.2	20.4	21.1	20.1	18.4	16.6	634.73	15.75	.0635	11.40	10.20
7. Reference	4–sp + Lock-up	11.1	21.0	20.9	19.6	17.2	15.1	644.69	15.51	.0645	9.69	8.77
8. Reference + Add-on's (6)	CVT	13.4	24.4	27.1	28.0	22.5	20.4	513.05	19.49	.0513	37.8	27.4
9. Reference + Add-on's (6)	4–sp + Lock-up	11.8	22.4	22.5	21.4	19.5	17.6	594.12	16.83	.0594	19.0	15.9
10. Diesel	STD	13.8	22.2	21.6	19.8	17.1	14.8	579.03	17.27	.0579	22.1	18.1
11. Diesel + Add-on's (6)	STD	15.3	25.4	25.2	23.5	21.0	18.3	502.66	19.89	.0503	40.7	28.9
12. Diesel	4-sp + Lock-up	14.6	26.1	29.6	26.4	23.1	19.3	496.35	20.15	.0496	42.5	29.8
13. Diesel	CVT	16.0	25.3	28.1	27.3	23.0	18.7	472.35	21.17	.0472	49.7	33.2
14. Diesel + Add-on's (6)	CVT	17.4	27.4	31.2	32.1	29.0	24.1	419.42	23.84	.0419	68.6	40.7
15. Diesel + Add-on's (6)	4-sp + Lock-up	16.1	30.0	34.1	31.4	27.7	24.2	429.63	23.28	.0430	64.6	39.2

TABLE 4–35 SUMMARY OF FUEL USAGE FOR ANNUAL TANK MILEAGE AND PERCENT IMPROVEMENT FOR COMPANY Y COMPACT SIZE VEHICLE (Without Air Conditioning)

Simulation Configuration	Type of Transmission	FDC Fuel Economy (mpg)	Steady-Speed Fuel Economy (mpg) 30	40	50	60	70	Total Gallons Used in 10,000 Miles Based on Tank Mileage Formula	Fuel Economy (mpg)	Fuel Usage (gpm)	% Improvement (mpg)	% Reduction (gpm)
1. Reference Co. Y Compact	STD	13.8	21.7	20.4	19.4	16.9	13.5	589.4	16.97	.0589		
2. Radial Tires Substituted	STD	14.1	22.8	21.3	20.1	17.7	14.0	569.64	17.55	.0570	3.42	3.22
3. 10% Less Weight	STD	14.4	22.6	21.0	19.9	17.5	13.8	568.45	17.59	.0568	3.65	3.56
4. 10% Less Frontal Area	STD	13.9	22.1	20.9	20.0	17.9	14.4	575.68	17.37	.0576	2.36	2.21
5. 20% Less Drag Coefficient	STD	14.1	22.5	21.4	20.8	18.9	15.4	560.20	17.85	.0560	5.19	4.92
6. Including All Add-on's (1-5)	STD	15.3	25.4	23.8	22.6	21.0	17.5	507.87	19.61	.0510	14.6	13.40
7. Reference	4-sp + Lock-up	15.6	25.8	22.8	19.7	17.9	15.6	531.51	18.81	.0532	10.8	9.68
8. Reference	CVT	17.4	29.6	29.0	25.8	19.4	16.7	459.67	21.75	.0460	28.2	21.9
9. Reference + Add-on's (6)	CVT	19.1	31.0	34.9	31.9	25.6	20.5	399.19	25.05	.0399	47.6	32.3
10. Reference + Add-on's (6)	4-sp + Lock-up	16.8	27.9	26.4	24.2	21.7	20.4	467.60	21.39	.0468	26.0	20.5
11. Diesel	STD	19.7	30.5	27.4	24.0	20.6	17.5	437.82	22.84	.0438	34.6	25.6
12. Diesel + Add-on's	STD	22.4	36.2	34.0	30.0	26.3	22.5	365.29	27.38	.0365	61.3	38.0
13. Diesel	4-sp + Lock-up	20.0	38.0	40.0	33.7	28.1	22.9	411.95	24.27	.0412	43.0	30.0
14. Diesel	CVT	23.8	38.1	38.1	32.8	27.1	22.1	344.42	29.03	.0344	71.1	41.6
15. Diesel + Add-on's (6)	CVT	26.1	42.3	43.4	41.0	34.2	28.0	297.99	35.56	.0298	97.8	49.4

4.3.10.3. Cost-Effectiveness Analysis

For each improvement we made estimates for the incremental plus-or-minus cost over reference vehicle for the initial investment and repairs plus our best estimate of incremental replacement cost for items such as radial tires versus belt bias tires, catalytic converters, spark plugs, etc. We recognized at the very beginning of our work that estimating the cost for devices, which in many cases had not reached the production prototype stage – and as far as we have been able to ascertain, this is true of most of the concepts listed – was subject to much controversy. Therefore, we approached this issue by trying to include only those items and costs which were different from the reference vehicle, using the mid-values of the owner costs as related by the innovators or derived intuitively.

We did not undertake the usual industrial engineering part-by-part cost analysis generally applied to components supplied to the engine and automotive industry, primarily because we did not know enough about the specifics of any one design concept, particularly so in light of production quantities approaching a million per year.

The methodology for developing the comparison is apparent from examining Tables 4-36 and 4-37. If the reader wishes to adjust the results based on different cost information, he may do so.

We chose a time period of 10 years – 100,000 miles – for the individual improvements, as we felt that this represented a life cycle period any improvement would have to meet to be satisfactory and to be considered as a candidate for inclusion in a synthesized vehicle design.

In the case of the synthesized vehicle we used two time frames, first ownership – 3 years and 50,000 miles – and 10 years and 100,000 miles – for a life cycle. In arriving at the miles travelled for each time period we considered the statistics developed[75-77] for first ownership, miles travelled per year, versus age of car, and the mandatory 50,000-mile durability test for emission controls.[78]

As discussed above, when an improvement is incorporated in a vehicle, it will affect both gas consumption savings and dollar savings over the course of the vehicle's lifetime. Thus, for the improvement to be beneficial, the savings that accrue over any period – up to and including the 10-year life expectancy of the car – should be greater than the initial investment in the improvement,

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75. Liston, L.L., and Gauthier, C.L., Cost of Operating an Automobile, Federal Highway Admin., U.S. Department of Transportation, April 1972.

76. Strate, H.E., Nationwide Personal Transportation Study, Report No. 2, Annual Miles of Automobile Travel, Federal Highway Administration, U.S. Department of Transportation, April 1972.

77. Energy-Related Studies Underway and Highway Travel Forecast Related to Energy Requirements, Report No. HHP-40, U.S. Federal Highway Administration, U.S. Department of Transportation, February 28, 1973.

78. New Motor Vehicles and New Motor Vehicle Engines, Control of Air Pollution, Federal Register, Vol. 37, No. 221, Part II, November 15,1972.

any maintenance and repair costs which would be associated with it, and, for example, as in the case of radial tires, any benefit that they may generate. Radial tires have the intrinsic benefit of being less costly than bias-ply tires when related to cost per mile of tire use. In this analysis we treated the savings generated by lower tire cost per mile as a separate entry in the calculations.

The relationships between the initial cost and the other related costs and/or benefits varies as a function of the improved gas consumption for each improvement or combination of improvements. The savings generated is directly proportional to the cost of gasoline, i.e., the higher the cost of gasoline, the greater the potential savings. Since it is expected that the cost of gasoline will increase over the next several years, we employed gas prices of $0.40, $0.50, $0.75, $1.00 and $1.25 to estimate the growth and net savings that would be achieved at these various gas prices.

Tables 4-36 and 4-37 present the results of this analysis. The dashed line entry on each table represents the breakeven price of gasoline for each improvement, or combination of improvements. This then is the minimum price for gas that will generate sufficient savings to offset all incremental costs for the improvement.

The uppermost line cuts through the table at a level of gasoline prices equal to or greater than those required for "breakeven." The "breakeven" point is interesting as a measure of whether or not an improvement should be considered, but it does not provide any real incentive for the automobile owner to invest in that improvement or combination of improvements. The "breakeven" point is analogous to putting money in one's mattress and, after a period of time, removing the money until all that was put in was taken out, i.e., all that was invested in the improvement was finally paid back in the form of savings.

A much better yardstick for measuring the benefit is to assign time value to money and use the present value method of cash flow analysis to compare relative benefits. All of that sounds rather lofty, but it means simply that before a customer is likely to purchase the improvement he will make conscious or unconscious comparisons against ways that he might spend or use his money. For example, an equivalent sum could be put into a savings account earning 5 or 6% interest. Over a period of 3 years or 10 years, the individual could withdraw money from the savings account at a rate equivalent to the savings that the improvement would generate. But in the case of the savings account, the money has been earning interest and the money removed in the third year has earned $1 for every $5 invested, money removed in the fifth year earns $1 for every $3 invested; and at the 10th year the last money remaining has earned almost $2 for every $3 originally invested.

It is only sensible that the owner of the automobile will expect at least a return on his original investment equivalent to the amount that he might earn in bank interest. Other purchasers may have higher expectations with percentages of 18% being an estimate of those higher expectations. While there may not be another form of an investment which can provide a similar return, viz., 18%, there are those that require this higher level of incentive before they would invest in such an improvement.

TABLE 4–36

STANDARD SIZE VEHICLE
SUMMARY OF INVESTMENT COST DATA FOR INDIVIDUAL IMPROVEMENTS MEASURED AGAINST A RANGE OF FUEL COSTS

		Type of Individual Improvement														
Definition of Costs		10% Red'tn in Frontal Area	20% Red'tn in Drag	10% Red'tn in Weight	Radial Tires	Total	Std. Engine Catalyst Opt. Spark	Lean Burn	Stoichiometric	Turbo Charge Engine	Stratified Charge Engine	Lt. Wt. Diesel	4-sp With Lock-up	CVT	Const. Speed Acc. Drive Without Air Cond.	Const. Speed Acc. Drive With Air Cond.
Initial Incremental Δ Cost	$	–	–	100	70	170	125	100	300	200	500	600	75	200	25	25
Total Δ Repair & Maint. Cost	$	–	–	–	–	–	100	100	300	300	300	–	–	–	–	–
Total Δ Replacement Cost	$	–	–	–	-60	-60	100	60	100	–	–	–	–	–	–	–
Total Δ Cost		–	–	100	10	110	325	260	700	500	800	600	75	200	25	25
Fuel Economy Improvement %		1.3	2.6	2.7	2.5	9.1	7.5	7.5	10	7.5	17.5	20.0	10.0	20	1.0	3.0
% Fuel Use Reduction (%FUR*)		1.2	2.4	2.5	2.3	8.4	6.8	6.8	9	6.8	15.0	16.5	9.0	16.5	.95	2.9
% FUR x 6880 = Gals. Saved		83	165	172	158	558	468	468	619	468	1032	1135	619	1135	65	200
Dollars Saved @ $0.40/gal.		33.20	66.00	68.80	63.30	223.20	187.20	187.20	247.60	187.20	412.80	454.00	247.60	454.00	26.14	80
Net Savings @ $0.40/gal.		33.20	66.00	-31.20	53.30	113.20	-137.80	-72.80	-452.40	-312.80	-387.20	-146.00	172.6	254.00	1.14	55.00
Dollars Saved @ $0.50/gal.		41.50	82.50	86.00	79.12	279.00	234.00	234.00	369.50	234.00	516.00	567.00	309.50	567.00	32.5	100.00
Net Savings @ $0.50/gal.		41.50	82.50	-14.00	69.12	169.00	-91.00	-26.00	-390.50	-266.00	-284.00	-33.00	234.50	367.00	7.50	75.00
Dollars Saved @ $0.75/gal.		62.20	123.75	129.00	118.69	418.50	351.00	351.00	464.25	351.00	774.00	851.25	464.25	851.25	48.75	150.00
Net Savings @ $0.75/gal.		62.20	123.75	29.00	108.69	308.50	26.00	91.00	-235.75	-149.00	-26.00	251.25	389.25	651.25	23.75	125.00
Dollars Saved @ $1.00/gal.		83.00	165.00	172.00	158.00	558.00	468.00	468.00	619.00	468.00	1034.00	1135.00	619.00	1135.00	65.00	200.00
Net Savings @ $1.00/gal.		83.00	165.00	72.00	148.00	448.00	143.00	208.00	-81.00	-32.00	232.00	535.00	544.00	935.00	40.00	175.00
Dollars Saved @ $1.25/gal.		103.70	206.25	215.00	197.81	697.50	585.00	585.00	773.75	585.00	1290.00	1418.75	773.75	1418.75	81.25	250.00
Net Savings @ $1.25/gal.		103.70	206.25	115.00	187.81	587.50	260.00	325.00	73.75	85.00	490.00	818.75	698.75	1218.75	56.25	225.00
Fuel Cost per Gallon to Breakeven Based on Total Δ Cost		–	–	$.58	$.06	$.20	$.69	$.56	$1.13	$1.07	0.78	$.53	$.12	$.18	$.38	$.13
Concept Described in Section		4.3.7	4.3.7	4.3.8	4.3.6		4.3.3.1	4.3.3.2	4.3.3.3	4.3.3.4	4.3.3.5	4.3.3.6	4.3.4	4.3.4.11	4.3.5	4.3.5

*FUR = Fuel Use Reduction

Assumptions:

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

Note: These lines define the gas price which satisfies the present value (greater than zero dollars) of future savings and costs criteria at a different % discount rates. See section 4.3.10.3 for details.

0% ————

6% - - - - - - -

10% — — —

18% —·—·—·—

TABLE 4–37

COMPACT SIZE VEHICLE
SUMMARY OF INVESTMENT COST DATA FOR INDIVIDUAL IMPROVEMENTS MEASURED AGAINST A RANGE OF FUEL COSTS

	Type of Individual Improvement:													
Definition of Cost	10% Reduction Frontal Area	20% Red'tn in Drag	10% Red'tn in Weight	Radial Tires	Total	Std. Engine Catalyst Opt. Spark	Lean Burn	Closed Loop Exhaust Emission Control System	Turbo-charged Engine	Stratified Charge Engine	Lt. Wt. Diesel	4-sp + Lock-up	CVT	Const. Speed Acc. Drive Without Air Cond.
Initial Incremental Δ Cost	–	–	80	60	140	125	100	300	200	400	500	65	150	25
Total ΔRepair & Maint. Cost	–	–	–	–	–	100	100	300	300	300	–	–	–	–
Total Δ Replacement Cost	–	–	–	-40	-40	100	–	100	–	–	–	–	–	–
Total Δ Cost	–	–	80	20	100	425	200	700	500	700	500	65	150	25
Fuel Economy Improvement %	2.11	4.22	3.4	3.5	13.2	7.5	7.5	10	7.5	18	25	15	25	1.
% Fuel Usage Reduction (% FUR)	1.97	3.96	3.2	3.3	12.4	6.8	6.8	9	6.8	15	20	13	20	.9
% FUR* x (5270 = Gals. in 10 yrs)	104	208	169	174	653	358	358	474	358	791	1054	685	1054	47
Dollars Saved @ $0.40/gal	42	83	67	70	261	143	143	190	143	316	422	274	422	19
Net Savings @ $0.40/gal	42	83	-27	50	161	-182	-57	-510	-357	-384	-78	209	272	-6
Dollars Saved @ $0.50/gal	50	104	84	87	327	179	179	237	179	396	527	343	527	24
Net Savings @ $0.50/gal	52	104	4	67	227	-146	-21	-463	-321	-305	27	278	377	-1
Dollars Saved @ $0.75/gal	78	156	126	130	450	269	269	356	269	593	791	514	791	35
Net Savings @ $0.75/gal	78	156	46	110	350	-56	69	-344	-231	-107	291	449	641	10
Dollars Saved @ $1.00/gal	104	208	169	174	653	358	358	474	358	791	054	685	1054	47
Net Savings @ $1.00/gal	104	208	89	154	553	23	158	-226	-142	91	554	620	904	22
Dollars Saved @ $1.25/gal	130	260	211	217	817	448	448	593	448	989	1318	856	1318	59
Net Savings @ $1.25/gal	130	260	131	197	717	123	248	-107	-52	289	818	791	1168	34
Fuel Cost/Gallon to Break Even Based on Total Δ Cost	–	–	.47	$ .27	.15	1.19	.56	1.48	$ 1.40	$.88	.47	.09	.14	.53
Concept Described in Section	4.3.7	4.3.7	4.3.8	4.3.6		4.3.3.1	4.3.3.2	4.3.3.3	4.3.3.4	4.3.3.5	4.3.3.6	4.3.4	4.3.4.11	4.3.5

*FUR = Fuel Use Reduction

Assumptions:

1. Compact size reference vehicle
2. Tank mileage = 18.97 mpg
3. 10 years = 100,000 miles = 5270 gallons gasoline used
4. Heavy horizontal black line indicates approximate breakeven point between investment and fuel cost/gallon
5. Δ = Difference between the reference vehicle and improvement idea
6. Net savings = total Δ cost – dollars saved at a fuel cost

Note:
0% ————
6% – – – – –
10% —— —— ——
18% —·—·—·—
These lines define the gas price which satisfies the present value (greater than zero dollars of future savings and costs criteria at different % discount rates. See section 4.3.10.3 for details.

In order to adjust for the expected return on the investment of 6, 10 and 18% we discounted the future savings (maintenance and repair costs, pro rata replacement costs, such as for tires and catalytic converters) in such a way that it appears mathematically that the money had earned the interest at the rate specified. This is called present value cash flow analysis and has been measured over 10 years (100,000 miles) and 3 years (50,000 miles) for every individual fuel consumption improvement device.

For an improvement to be justified when using one of the three discounted rates the present value of all future savings, when discounted back to the present, must be greater than the initial investment. Using gas prices of $0.40, $0.50, $0.75, $1.00, and $1.25, we determined at what gas price the improvement would return an equivalent amount of interest. Three additional lines, in addition to the upper "breakeven" line, have been added to each table. These lines successfully represent 6%, 10% and 18% discounts and indicate at which level of gasoline price the improvement will return the desired interest rate. It will be noticed that, in many cases, the three discount rates all occupy the same gas price. This indicates that the increment between gas prices, i.e., $0.40 to $0.50, was large enough to embrace all three discount factors. For example, had smaller increments in gasoline prices, such as a $0.01 addition been used, then the lines could all be separated.

Since there is substantial uncertainty relating to some of the values for fuel economy improvement, incremental initial repair, replacement, and maintenance cost, employed in this analysis, we did not use, nor did we attempt to accommodate inflation and/or the changes in gas price that might occur over the analysis period of either 3 or 10 years. While such adjustments would be interesting, they would not likely add any additional knowledge to our analysis and for that reason we ignored them. We can also see that the catalytic converter approach to emission control being offered for 1975 models is questionable from a cost-effective standpoint. That is to say, if after the first owner pays a minimum of $125 incremental initial cost, and also spends $10/year additional for yearly tune-up to prevent fouling the converter, replaces the catalyst at 50,000 miles at a cost of $100, he will just break even at 100,000 miles and 10 years, providing gasoline has *averaged* approximately $0.70/gal, if he owns a standard size car, or $0.90/gal, if he owns a compact, and this is for a 10-year ownership period.

Furthermore, the closed-loop exhaust control system is even less cost-effective and, while we should not be considering this approach for this study, we feel it represents a possible stop-gap solution until other long-term approaches are developed. It appears to have only a relatively short-term potential, however, unless marked gains can be made over our estimates or pollution standards are relaxed beyond the interim 1975 levels.

The lean burn engine concept (described in Section 4.3.3.2) has also been included as a means of improving fuel economy because of its potential as a promising cost-effective solution available for adaptation in near term. We chose the Ethyl Corporation approach as a typical example for comparison with other approaches such as stratified charge diesel, etc., because of the relative simplicity of the carburetor, thermal reactor, and its ready adaptability to a standard engine when fully developed. We do not necessarily advocate this system, although the emission results are improving with the effort being applied (see Appendix for latest data).

The turbo charged engine does not appear to be cost-effective and, while we finished the individual evaluation of this concept, we did not consider it for incorporation into a synthesized vehicle system.

The stratified engine, as an individual improvement, is marginally cost-effective, based on our cost analysis. Because of sensitivity to first cost and repair estimates, we felt the concept should be included and evaluated in a synthesized vehicle system.

The diesel engine, as an individual improvement, is more cost-effective than the stratified engine, and has been included and evaluated further.

Four-speed automatic transmissions with torque lock-up or continuously variable transmissions, when matched properly to any of the internal combustion engine concepts, are very cost-effective innovations. Tables 4-36 and 4-37 indicate the potential savings when these improvements are matched to the standard engines used in the reference vehicles. In Chapter V we will show the estimated benefits when matched to each of the engine concepts.

Constant speed accessory drives for vehicles not equipped with air conditioning do not be cost-effective since the estimated savings in fuel are approximately 6-7 gallons/year. The estimated saving if used to drive an air conditioner operating on a 1/3 duty cycle is approximately 20 gallons/year and therefore would also be a very marginal saving and we have not considered this innovation for the synthesized vehicle system.

4.3.11. Summary Analysis of Individual Improvements Against Qualitative and Quantitative Constraints

The general discussion in this subsection covers Tables 38-46 – *Summary Analysis of the Individual Improvements against the Qualitative and Quantitative Constraints for Both Compact and Standard Size Vehicles* – which have been 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 agains 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 will be used in each synthesized designed vehicle covered in Chapter 5. 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 4-40, which also shows the estimated gains for each of the complete systems.

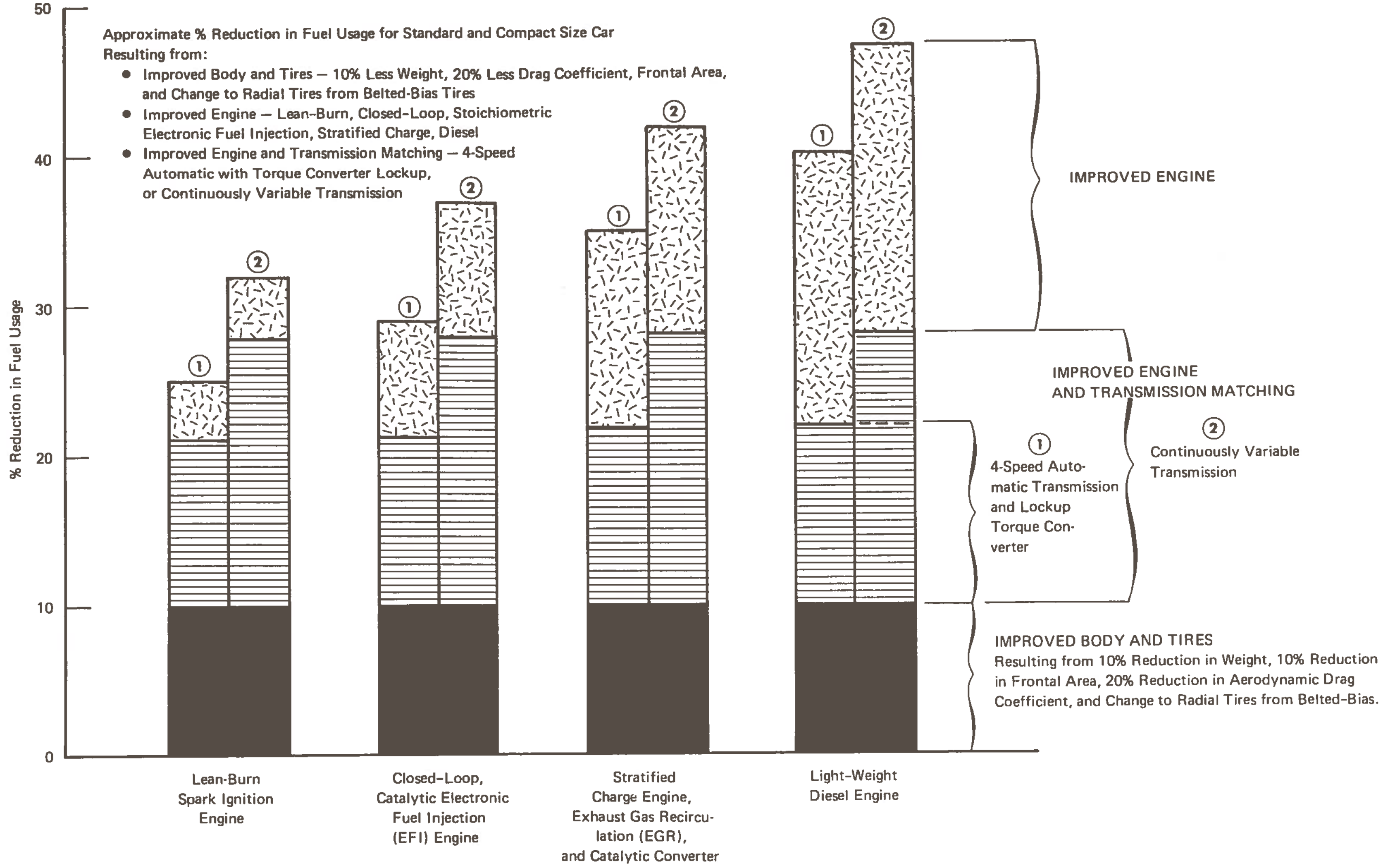
4.3.11.1. Improved Light-weight Body and Chassis and Use of Radial Tires

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 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.

4.3.11.2. 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 would have to be considered a high technical risk, and is unproven beyond the concept stage. Furthermore, the changes required in the design and construction of such an engine – optimally loaded for best specific fuel consumption – to provide durability under prolonged operating



① Synthesized vehicle with 4-speed automatic transmission and torque converter lock-up

② Synthesized vehicle with continuously variable transmission

FIGURE 4—40 REDUCTION IN FUEL USAGE FROM PROPOSED IMPROVEMENTS 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.

4.3.11.3 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.

4.3.11.3.1 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. 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, in the interim, 1975 and 1976 emission standards can be met, but not the original 1976 and 1977 standards. See Appendix I, Section 6, for data referring to various lean-burn concepts.

4.3.11.3.2 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 S ction 4.3.11.3.1 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 composition 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. 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.

4.3.11.3.3 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 works 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 sub compact 1973 CVCC Honda introduced in Japan will probably set the pace for full scale introduction of this concept in the U.S. We do not believe this concept will be available before the 1980-1982 period on domestic vehicles.

4.3.11.3.4 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 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. However, while the prechamber diesel avoids the high rates of pressure rise (diesel knock), the economy potential as compared to the direct injection processes is lower. 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 an 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. In its regard we see no difficulty in meeting the interim 1976 emission standards.

5. THE SYNTHESIS AND EVALUATION OF ALTERNATIVE VEHICLE DESIGNS

5.1. INTRODUCTION

In this chapter the method used to synthesize various alternative vehicle designs incorporating the individual improvements discussed and evaluated in Chapter 4 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.

5.2. DESCRIPTION OF SYNTHESIZED ALTERNATIVE VEHICLE DESIGNS

5.2.1. Vehicle Designs

Table 5-1 lists the various synthesized alternative vehicle designs by type of engine, type of transmission, and size of vehicle. The table shows that 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 converter 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.

5.2.2. General Description of Vehicles

As described in Section 1.2 the standard-size vehicle weighs between 3800 and 4200 pounds, has a two-door, hardtop body, and is capable of performing or 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 options include 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 5–1
LIST OF 16 LIGHTWEIGHT 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.

5.2.3. Innovative Improvements Common to All Vehicle Designs

As discussed in Section 4, 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, and
4. substitution of radial tires for conventional belted bias tires.

The individual contribution to fuel economy improvement for each of these approaches was discussed in Section 4.

5.2.4. Engine and Transmission Improvement

In Section 4 each engine improvement type was examined 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. In this section we have 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.

5.3. SIMULATION OF VARIOUS SYNTHESIZED VEHICLES

Our approach in determining the improvement in fuel economy or percentage reduction in fuel usage was much the same as that described in Section 4; that is, where possible, actual experimental data, as furnished by the innovators, were used 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 study-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.

5.4 SUMMARY OF RESULTS AND COSTS

5.4.1 Fuel Economy Gains and Costs

Tables 5-2 and 5-3 consists of three lines of demarcation as shown by the three horizontal sections. Section 1 related to initial increment costs for each design over the sticker price for the reference vehicles. 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 miles) 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. 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, their 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 5-2 and 5-3 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.

TABLE 5-2

COMPACT SIZE VEHICLE

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

Section	Definition of Cost	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.	
		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 △ 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	–	–	–	–
	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
2	Fuel Economy Improvement %	31	31	41	41	35	35	45	45	42	42	52	52	50	50	60	60
	% 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
3	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
	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

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*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 5-3

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

Section	Definition of 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.	
		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% -·-·-·-	

Table 5-2 and 5-3 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 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 of 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.

5.4.2. 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 5-2 and Table 5-3.

- *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 for the 1977 to 1980 period, the lean-burn concept, would be the most cost-effective system to develop, 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.

5.5 SYSTEM COMPARISON BETWEEN SYNTHESIZED VEHICLE DESIGNS

Table 5-4 summarizes the potential improvements of both the compact and standard size vehicles, as described in Section 5.2.1 and Table 5-1. 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

TABLE 5-4

SUMMARY OF POTENTIAL IMPROVED COMPACT AND STANDARD SIZE VEHICLES*

	STANDARD SIZE								COMPACT SIZE			
VEHICLE CONCEPT	% 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	REMARKS	% 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:								● 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				
4-Speed Automatic and Torque Converter Lockup Transmission	24	20	1376	662	Low	1978-1981	*		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								● 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				
4-Speed Automatic and Torque Converter Lockup	36	30	2064	538	High	1982-1984	* Good Results to Date		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								● 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				
4-Speed Automatic Transmission and Torque Converter Lockup	44	36	2476	1046	Medium	1982-1984	*NO_x May Present Problem.		50	40	2084	899
or Continuously Variable Transmission	60	46	3164	1462	High	1982-1984			60	47	2448	1086

* 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 is presently being contemplated for the future. We recognize that this concept, as 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 of 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.

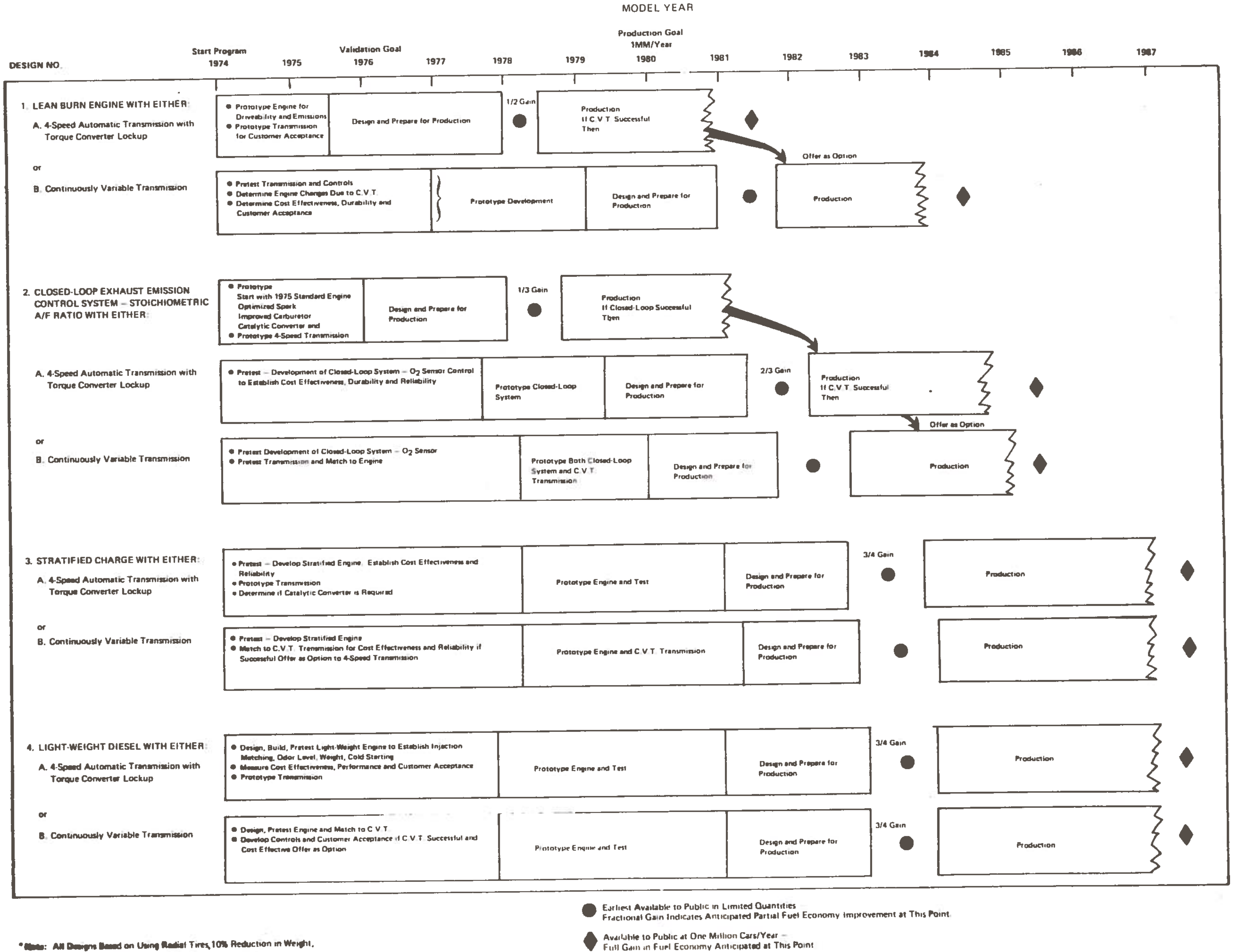
5.6 DESIGN VEHICLE TIMETABLE

Table 5-5 – Possible Evolutionary Timetable for Introducing Synthesized Design Vehicles – is another way of showing the time scales previously discussed. For this study we assumed a starting date of 1974 and have shown the necessary time span surmised necessary (1) to prove the concept and develop the prototype and (2) to design and prepare for production, and (3) to start production on a limited scale so that the concepts could be proven by the public. We anticipate that at the start of this limited production the fuel economy gains would vary as shown for different concepts from one-third to three-quarters of the total anticipated gains. This is shown by the black round dot on the chart. After production starts on a limited basis, we then show a buildup to 1,000,000 cars a year with full fuel economy gains. This point is shown by a black diamond.

For each of the engine concepts, we have shown two alternate transmission choices. Again, we have shown that the four-speed transmission would be available before the continuously variable transmission. If both of these transmissions were started in parallel, then if the continuously variable transmission proved effective and reliable, we forsee this transmission being offered as an option. This is shown as an arrow leading from the four-speed transmission alternative to the continuously variable transmission alternative.

In the case of the stratified charge and light-weight diesel concepts, we feel that by the time that either of these engines was fully developed the answer as to whether the continuously variable transmission was usable and effective would be obtained. Therefore, either of these engines could be equipped with the continuously variable unit.

POSSIBLE EVOLUTIONARY TIMETABLE FOR INTRODUCING SYNTHESIZED DESIGN VEHICLES*



*Note: All Designs Based on Using Radial Tires, 10% Reduction in Weight, Frontal Area, and 20% Reduction in Aerodynamic Drag

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

Tables 4-38 through 4-46

		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	4.3.6	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)

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%	.95	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 Facilitiesif 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 or 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 0°F 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