Reference Copy

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# AUTOMOTIVE ENERGY EFFICIENCY PROGRAM

Papers Presented at the

# PROJECT COORDINATION MEETING

November 4-6, 1975

Sponsored by

U.S. DEPARTMENT OF TRANSPORTATION

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16. Abstract

This volume contains working papers presented at the Project Coordination Meeting of the Automotive Energy Efficiency Program held at the DOT Transportation Systems Center, November 4-6, 1975. This program is the Federal Government's major effort to assess the capability of the automotive industry to significantly improve the fuel economy of production vehicles and assess the related socio-economic effects.

The primary objective of the conference was to report on progress to date and future plans of the AEEP as well as to promote the exchange of information between government, industry, and university investigators.

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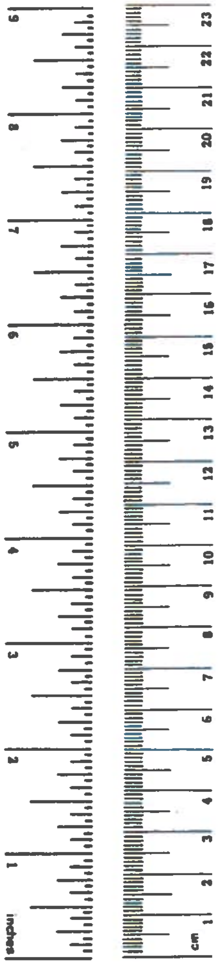
# METRIC CONVERSION FACTORS

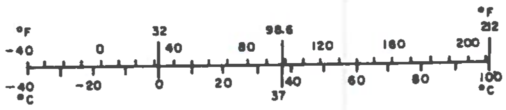
## Approximate Conversions to Metric Measures

| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | 2.5 | centimeters | cm |
| ft | feet | 30 | centimeters | cm |
| yd | yards | 0.9 | meters | m |
| mi | miles | 1.6 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 6.5 | square centimeters | $cm^2$ |
| $ft^2$ | square feet | 0.09 | square meters | $m^2$ |
| $yd^2$ | square yards | 0.8 | square meters | $m^2$ |
| $mi^2$ | square miles | 2.6 | square kilometers | $km^2$ |
| | acres | 0.4 | hectares | ha |
| | | **MASS (weight)** | | |
| oz | ounces | 28 | grams | g |
| lb | pounds | 0.45 | kilograms | kg |
| | short tons (2000 lb) | 0.9 | tonnes | t |
| | | **VOLUME** | | |
| tsp | teaspoons | 5 | milliliters | ml |
| Tbsp | tablespoons | 15 | milliliters | ml |
| fl oz | fluid ounces | 30 | milliliters | ml |
| c | cups | 0.24 | liters | l |
| pt | pints | 0.47 | liters | l |
| qt | quarts | 0.95 | liters | l |
| gal | gallons | 3.8 | liters | l |
| $ft^3$ | cubic feet | 0.03 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.76 | cubic meters | $m^3$ |
| | | **TEMPERATURE (exact)** | | |
| °F | Fahrenheit temperature | 5/9 (after subtracting 32) | Celsius temperature | °C |



## Approximate Conversions from Metric Measures

| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.04 | inches | in |
| cm | centimeters | 0.4 | inches | in |
| m | meters | 3.3 | feet | ft |
| m | meters | 1.1 | yards | yd |
| km | kilometers | 0.6 | miles | mi |
| | | **AREA** | | |
| $cm^2$ | square centimeters | 0.16 | square inches | $in^2$ |
| $m^2$ | square meters | 1.2 | square yards | $yd^2$ |
| $km^2$ | square kilometers | 0.4 | square miles | $mi^2$ |
| ha | hectares (10,000 $m^2$) | 2.5 | acres | |
| | | **MASS (weight)** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.2 | pounds | lb |
| t | tonnes (1000 kg) | 1.1 | short tons | |
| | | **VOLUME** | | |
| ml | milliliters | 0.03 | fluid ounces | fl oz |
| l | liters | 2.1 | pints | pt |
| l | liters | 1.06 | quarts | qt |
| l | liters | 0.26 | gallons | gal |
| $m^3$ | cubic meters | 35 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.3 | cubic yards | $yd^3$ |
| | | **TEMPERATURE (exact)** | | |
| °C | Celsius temperature | 9/5 (then add 32) | Fahrenheit temperature | °F |



# PREFACE

This volume contains working papers presented at the Project Coordination Meeting of the Automotive Energy Efficiency Program held at the DOT Transportation Systems Center, November 4-6, 1975, chaired by Harold Miller of TSC, and coordinated by Ruth Hunter of TSC. This program is the Federal Government's major effort to assess the capability of the automotive industry to significantly improve the fuel economy of production vehicles and assess related socio-economic effects.

The primary objective of the conference was to report on progress to date and future plans of the Automotive Energy Efficiency Program and to promote the exchange of information between government, industry, and university investigators. The studies reported in the last three papers in this volume were supported by the DOT's Office of University Research.

Thirty papers and illustrated lectures were presented at the conference, 22 of which are included in this publication. Eight papers which were presented at the conference were not submitted for publication. Abstracts were available for five of these eight papers, and are included.

The Program Office appreciates the cooperation of the various authors and contractors who helped to make this conference a success. There were approximately 150 registered attendees at this conference as well as many non-registered TSC employees who attended lectures pertinent to their work areas.

# AGENDA

### 3 November 1975

6:00 PM

Preregistration and Reception – Copley Plaza Forum Room

### 4 November 1975

Auditorium Transportation Systems Center

9:00–9:45 AM

**Opening Remarks**

Robert Whitford, Acting Director TSC

Richard Strombotne, Chief, Energy & Environment Division Office of the Secretary of Transportation

9:45–10:15 AM

**ERDA Program**

George Thur – ERDA

10:15–10:35 AM – COFFEE

**COMPONENT EVALUATION SUBPROJECT**

10:35–10:50 AM

Herbert H. Gould – TSC

**Road Load Reduction**

10:50–11:20 AM

Auto Weight Reduction – Dartmouth

11:20–11:50 AM

Tire Resistance Measurements – CALSPAN

11:50–12:20 PM

Tire Rolling Resistance Analysis – University of Michigan

12:20–12:50 PM

Evaluation of Bus Aerodynamic Add-On Device – Purdue

12:50–1:50 – LUNCH

**Engine-Roadload Matching**

1:50–2:20 PM

Prototype Transmission Evaluation – ADL

**Engine Evaluation**

2:20–2:50 PM

Production Engine Evaluation – BERC

2:50–3:10 PM – COFFEE

3:10–3:40 PM

The Effect of Variations in Emission Control Systems on Automotive Fuel Economy – JPL

3:40–4:10 PM

Performance Evaluation Criteria for Lean Operating SI Engines – MIT

## 4 November 1975 (Cont)

4:10–4:40 PM
Evaluation of Engine Control Parameters – Aerospace Corp.

**Fuels, Energy Storage and Retrofit Devices**

4:40–5:10 PM
Assessment of Hybrid Systems – Aerospace Corp.

## 5 November 1975

9:00–9:30 AM
Automotive Fleet Impacts on Refinery Operations – Stanford Research Institute

9:30–10:00 AM
Evaluation of Lithium Sulfur Batteries for Automobiles – Argonne National Laboratory

10:00–10:30 AM
Automotive Retrofit Devices – Aerospace Corp.

10:30–10:45 AM – COFFEE

### AUTOMOTIVE MANUFACTURING AND MAINTENANCE SUBPROJECT

10:45–11:00 AM
Samuel Powel – TSC

11:00–11:45 AM
Existing Manufacturing System – Boston University and Rath and Strong

11:45–12:30 PM
Auto Manufacturing Assessment System – Corporate Tech Planning

12:30–1:30 PM – LUNCH

1:30–2:00 PM
Historical Data – Clayton

2:00–2:30 PM
Service and Repair Data Base – ADL

2:30–3:00 PM
Mfg. Technology Assessment – Pioneer

3:00–3:15 PM – COFFEE

3:15–3:45 PM
Automotive Scrappage and Recycling Industry – H.H. Aerospace

### FLEET ANALYSIS

3:45–4:05 PM
Fleet Analysis, Analysis Process – Terry Kendall, TSC

4:05–4:30 PM
Assessment State-of-the-Art Projection Models – Environmental Impact Center, Inc.

4:30–5:00 PM
Driver's Aid Survey – Aerospace Corp.

## 6 November 1975

9:00–9:20 AM
Automotive Fuel Economy Data Base – Bill Basham, TSC

### MARKET AND MOBILITY PROJECTIONS SUBPROJECT

9:20–9:35 AM
Ron Mauri, TSC

9:35–9:50 AM
Automobile Demand Analysis – Wharton

9:50–10:05 AM – COFFEE

10:05–10:30 AM
Car Purchase Behavior – ADL

10:30–11:00 AM
Automotive Resource Requirements Simulation – Draper Laboratory

### TEST AND EVALUATION SUBPROJECT

11:00–11:15 AM
Robert Wilmarth, TSC

11:15–11:45 AM
Study of Tech. Improvements, Auto Fuel Consumption – SWRI

11:45–12:15 PM
Fuel Flow Test Program – NBS

12:15–1:15 PM – LUNCH

### UNIVERSITY RESEARCH

1:15–1:25 PM
University Research Program – Terry Brown, Office of University Research

1:25–1:50 PM
J. David Powell – Stanford University

1:50–2:15 PM
Joseph S. Drake – University of Pittsburgh

2:15–2:40 PM
Richard T. Johnson – University of Missouri at Rolla

2:40–3:05 PM
Joseph L. Smith, Jr. – Massachusetts Institute of Technology

3:05–3:30 PM
Norman H. Beachley – University of Wisconsin

3:30–3:40 PM
Closing Remarks by Harold G. Miller, TSC

## CONTENTS

## CONTENTS (CONT'D)

# AUTO WEIGHT REDUCTION

F. J. Hooven
Dartmouth College
Hanover, N.H.

## ABSTRACT

Design studies are presented of weight-conscious 4, 5, and 6 passenger vehicles. These are vehicles of conventional design and materials, but without weight penalties for styling or non-functional size. They are intended as a baseline from which the cost of styling and non-functional size may be determined.

Component weights are classified in terms of their product function, and statistical studies are reported of the weights of various component functional groups of actual vehicles.

Analytical relationships are derived from which the overall-vehicle weight effects of individual component weight changes may be determined.

# AUTOMOBILE TIRE ROLLING RESISTANCE MEASUREMENT PROGRAM

D. J. Schuring and K. D. Bird

Calspan Corp.
Buffalo, N.Y.

## ABSTRACT

A short discussion of tire power losses as related to automobile fuel consumption is followed by a review of the problems associated with obtaining accurate rolling resistance data. The Calspan program objectives are:

- Selection of a representative tire sample of about 30 tires
- Investigation of accuracy requirements for meaningful comparisons of power losses between tires
- Demonstration of a reliable test method
- Development of a short test procedure
- Determination of rolling resistance as a function of various tire performance variables.

Sample test results are presented showing the influence of tire temperature, road curvature (drum vs. flat belt), slip angle, torque, load, speed, and inflation pressure on rolling resistance for bias ply, bias belted, and radial ply tires, and tentative conclusions regarding future testing are offered.

# TIRE ROLLING LOSS ANALYSIS

Richard N. Dodge
University of Michigan
Ann Arbor, Michigan

## ABSTRACT

The phenomena of rolling resistance of a pneumatic tire is discussed from the point of view of its physical origin – primarily material hysteresis loss. This is highly dependent on tire temperature, which in turn depends on running time and vehicle driving cycles. We are currently analyzing experimental data to define the relationship between equilibrium values and initial or ambient temperatures. There are major differences in these which reflect directly on fuel consumption.

Measuring methods currently available for rolling resistance do not lend themselves directly to accurate measurement for highway use. It is necessary to interpret dynamometer or drum measurements in order to convert values obtained from them to values of rolling loss on the highway. Considerable progress has been made and we believe it is now possible to directly correlate such readings to the appropriate highway values. Present emphasis is on understanding the role of various tire design parameters in the rolling loss process.

The University of Michigan program on analysis of rolling resistance phenomena began with a thorough literature survey of available information on this topic. A summary report was issued in July 1974 giving important results which were known to that time. Specifically, these dealt with data reported in the literature on such effects as load, speed, pressure and some tire construction details. Among other major considerations clarified in this report was the fact that practically all of the rolling loss phenomena can be ascribed to hysteresis of the tire materials themselves, and of those, the rubber components appear to play the dominant part.

We now know that the rolling loss phenomena is highly dependent upon the temperature in the tire, which in turn is dependent on the amount of rolling loss and the heat transfer characteristics of the tire itself. For example, Fig. 1 shows a typical plot of tire rolling loss versus time, where it may be seen that the initial, or ambient temperature, value of the rolling loss is significantly higher than the rolling loss observed after the tire has come into thermal equilibrium. Basically, this curve has the form of an exponential decay, and so has associated with it a typical relaxation time or time for equilibrium to be attained.

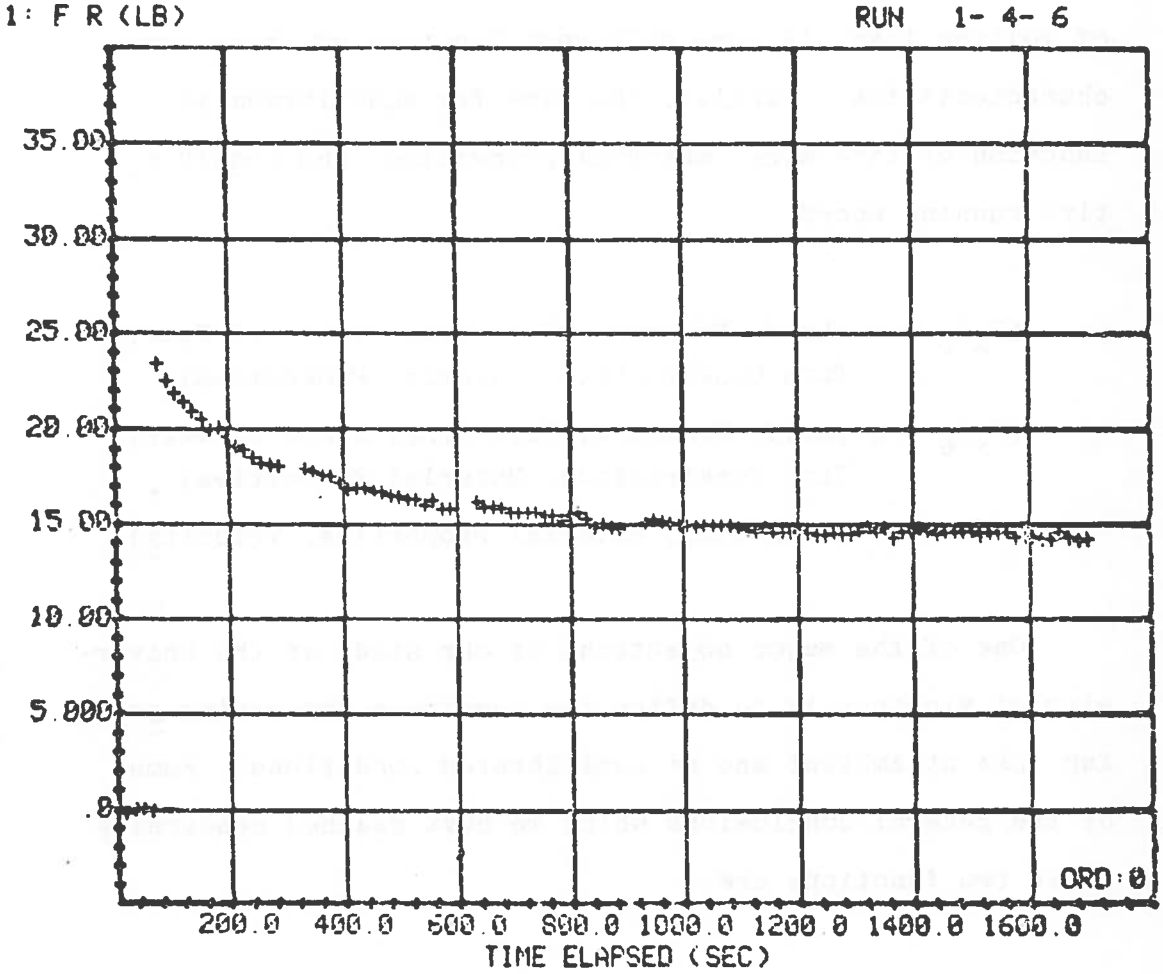


Figure 1. Typical Plot of Tire Rolling Loss Vs. Time

We know that the initial rolling loss is a function of tire load, pressure, size, state of wear, construction and material properties. We believe that the equilibrium value of rolling loss, is some different function of these same characteristics. Finally, the time for equilibrium is a function of tire size, material properties, and possibly tire running speed.

$(F_x)_0$ = f (Load, Pressure, Tire Size, State of Wear, Tire Construction, Material Properties).

$(F_x)_e$ = g (Load, Pressure, Tire Size, State of Wear, Tire Construction, Material Properties).

$\tau$ = $\tau$ (Tire Size, Material Properties, Velocity).

One of the major objections of our study at the University of Michigan is to define the functions describing rolling loss at ambient and at equilibrated conditions. Some of the general conclusions which we have reached concerning these two functions are:

(a) $(F_x)_0$ and $(F_x)_e$ are essentially independent of velocity for moderate speeds (< 55 mph), and of the order $1\% < (F_x)_e < 2\%$ load carried.

(b) For most passenger car tires

$$.5(F_x)_0 < (F_x)_e < .6(F_x)_0$$

Hence differences between the two are major.

(c) The time for equilibrium is of the order of $\tau \approx 30$ minutes for passenger car tires.

(d) Radial tires exhibit lower $F_x$ than bias or bias-belted tires.

Due to the large differences between rolling loss at the ambient and equilibrated states, one must be careful in the definition of rolling loss to decide which of these two values is the proper one to use. This would be particularly important in the construction of computer simulated driving cycles involving fuel consumption.

Another of our major efforts has to do with understanding measuring techniques for tire rolling loss. Industry usually measures rolling loss on curved drums, or flywheel type dynamometers, since that equipment is readily available in most tire development departments. We are currently working to correlate the curved drum to flat surface measurements. Our effort is an analytical one paralleling an experimental effort being carried out by a committee made up of major tire and automobile manufacturers under sponsorship of the Society of Automotive Engineers. Our conclusions mainly have to do with the relationship between the rolling loss measured on a flat surface or roadway and the corresponding rolling loss measured on a curved drum. This is illustrated in Figure 2. We find evidence from analysis and from test data that the comparison of rolling loss on the curved drum with rolling loss on the flat surface is a complex problem, for two reasons:

(a) The tire experiences higher stresses and hence greater hysteresis from running on a curved drum: For example, carrying the same load, a tire will run hotter on a curved drum than on a flat surface.

(b) The measured force on a curved drum may interact with the load on the tire since the tire is an elastic body, not a rigid one.

While we are currently attempting to construct an analytical framework in which to study this problem carefully, preliminary analysis indicates that for all mathematical models so far examined, the combined result in (a) and (b) above is that the rolling loss on a flat surface may be connected to the rolling loss as measured on a drum through the relationship $F_x = (F_x)_D \, (1 + \frac{d}{D})^{1/2}$ where d represents the tire diameter, D the drum diameter, $F_x$ the true rolling resistance on a flat surface or a road and $(F_x)_D$ the rolling resistance measured on the drum of diameter D.

This means that measured values of rolling resistance on a drum are smaller than the true values.

This is well illustrated by comparing the predictions made from the expression just shown with the data taken from the recent CALSPAN test, where rolling resistance was measured on a flat surface and on a 67" diameter drum using idential tires and identical force measuring equipment. This is shown in Table 1.

As a further part of our analytical work, we have completed an analysis for the time necessary for the tire to reach thermal equilibrium. To a first approximation this is given by $\tau \simeq 500\ \ell^2$ sec. where $\ell$ is maximum section thickness in centimeters, as shown in Figure 3. From this same analysis we know that the decay of rolling resistance with time is approximately a negative exponential, consistant with a normal heat conduction solution.

We are currently collecting and analyzing data to allow us to determine more exactly the influence on rolling resistance of such operating variables as

| | | | |
|---|---|---|---|
| (a) | load | (d) | tire size and design |
| (b) | pressure | (e) | state of wear |
| (c) | deflection | (f) | material properties |

In effect, we are attempting to define exactly the function f and g previously mentioned.

For this, we are currently using data from the earlier CALSPAN test previously reported here today, data from industry sources such as the SAE sponsored round robin test currently in progress among the various tire and automobile

## TABLE 1. COMPARISON OF PREDICTED $(F_{x_D}/F_x)$ AND MEASURED $(F_{x_D}/F_x)$

D = 67 in.

| TIRE | d | Predicted | Measured Values at t = 1695 sec. | | Measured |
|---|---|---|---|---|---|
| | | $(1+\frac{d}{D})^{-1/2}$ | $(F_{x_D})_m$ | $(F_x)_m$ | $\frac{(F_{x_D})_m}{(F_x)_m}$ |
| A78-13 Bias | 23.46 | 0.861 | 11.86 | 13.66 | 0.868 |
| G78-14 Bias | 27.06 | 0.844 | 17.25 | 21.11 | 0.817 |
| H78-15 Bias | 28.36 | 0.838 | 17.39 | 20.57 | 0.845 |
| A78-13 Bias-Belt | 23.46 | 0.861 | 11.74 | 13.30 | 0.883 |
| G78-14 Bias-Belt | 27.06 | 0.844 | 14.75 | 17.34 | 0.851 |
| L78-15 Bias-Belt | 29.30 | 0.834 | 18.71 | 23.40 | 0.800 |
| BR78-13 Radial | 23.88 | 0.859 | 8.44 | 9.52 | 0.886 |
| GR78-14 Radial | 26.86 | 0.845 | 11.88 | 13.97 | 0.850 |
| LR78-15 Radial | 29.08 | 0.835 | 13.30 | 17.07 | 0.780 |

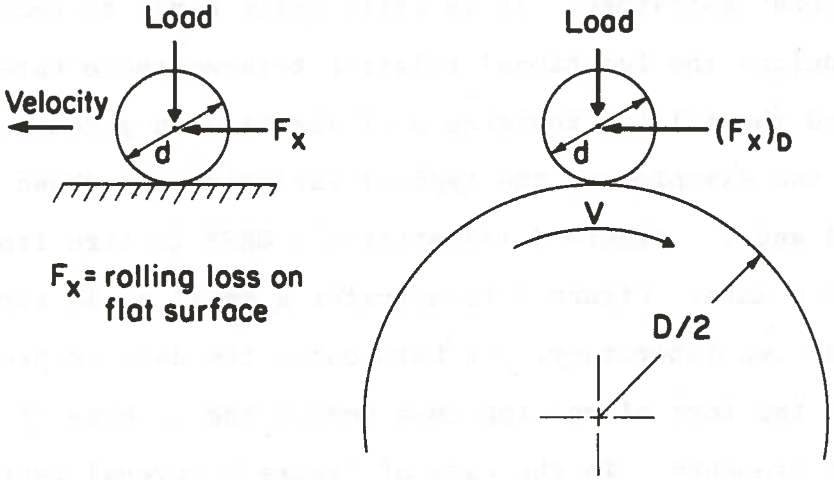


Figure 2. Geometry of Rolling Loss Measurement

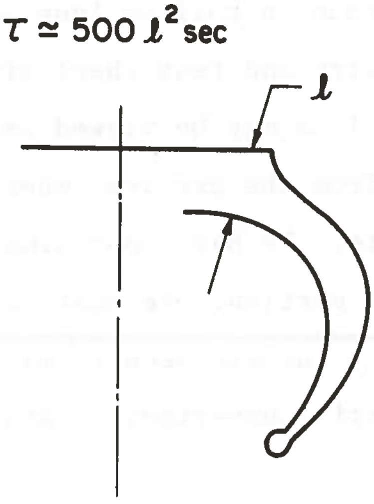


Figure 3. Approximate Time to Reach Thermal Equilibrium for a Rolling Tire

manufacturers, and finally, data taken on small scale tires from our own laboratory. It is still quite early to completely define the functional relation between these variables and the rolling resistance of the tire in general. However, two examples of the type of variation are shown in Figures 4 and 5. Figure 4 illustrates a BR78-13 tire from round robin data. Figure 5 illustrates a small scale tire run in our own laboratory. In both cases the data is presented in the form of rolling loss versus the inverse of inflation pressure. In the case of Figure 5 several vertical loads were applied to the tire. In general the similarities between the data taken on the thirteen inch tire and the data taken on the small scale tire are apparent.

Finally, to conclude this presentation we are currently devoting most of our effort to developing analytical expressions for the influence on rolling loss of load, inflation pressure, tire geometry and test wheel size. We believe that the total tire loss may be viewed as the sum of losses from the tread and from the carcass, where the carcass is a cord-rubber composite. We have approximate expressions for the stresses in each portion. We must refine these expressions and then relate the stresses to material losses. This will require substantial experimental and analytical effort.

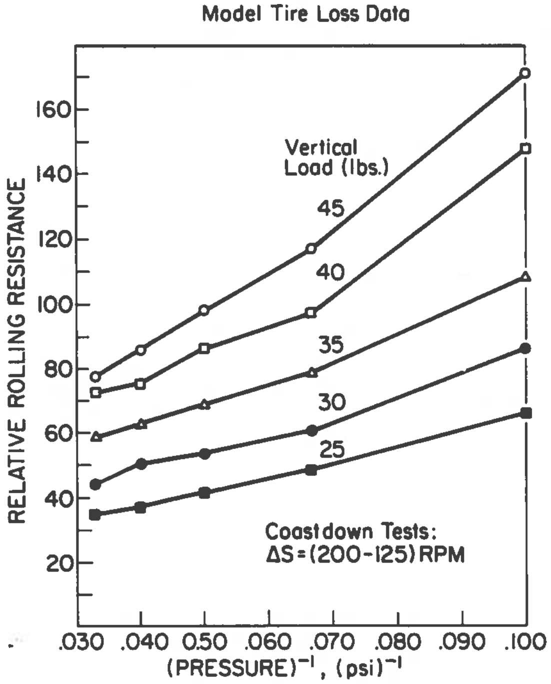


Figure 4. Rolling Resistance Measurements of a Single Tire at Two Cold Inflation Pressures (Tests Run at Four Different Laboratories)

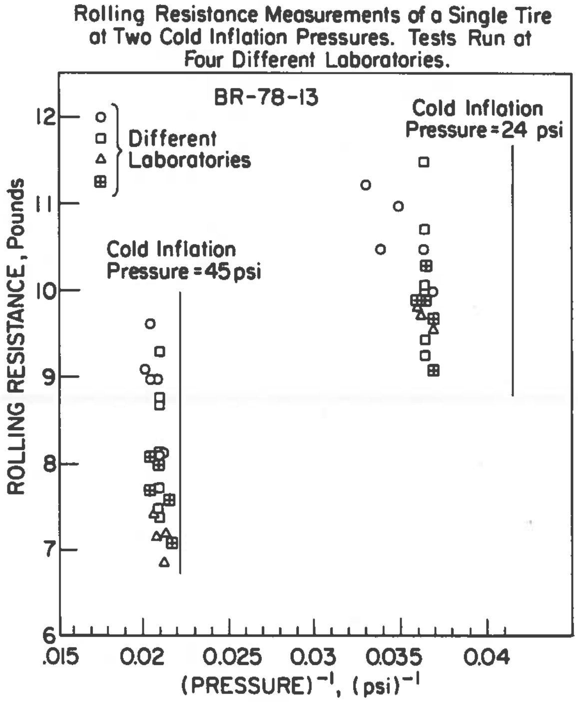


Figure 5. Relative Rolling Resistance Vs. Reciprocal of Inflation Pressure for Various Vertical Loads

# EVALUATION OF BUS AERODYNAMIC ADD-ON DEVICES

G. M. Palmer
Purdue University
West Lafayette, Indiana

## ABSTRACT

An experimental program is underway at Purdue to investigate methods of reducing the aerodynamic resistance of buses – specifically the Motor Coach Industries MC-7 and MC-8 configurations. The project involves both wind tunnel and full scale vehicle testing. The goal is to evaluate a variety of add-on devices or minor contour changes to the baseline vehicles which will reduce aerodynamic drag, and indicate guidelines for more efficient future designs. The wind tunnel test program basically involves force measurement and flow visualization studies of 1/16 scale models with various front and rear end add-on devices/contour changes using a fixed auxiliary ground plane to eliminate tunnel wall boundary layer effects. Progress to date indicates that no practical rear end add-on device produces significant drag reduction and, therefore present work has concentrated on front end modifications. Current tests indicate that the most promising technique for reducing drag on the MC-7 configuration is a large front radius roof fairing (a 22% reduction in drag with this fairing has been demonstrated so far). Turning vanes have produced negligible effect on the MC-7, however the cleaner shape of the MC-8 which has much sharper corner radii may show these devices to have some advantage. Tuft tests on a full scale MC-7 in actual road tests have verified the flow field characteristics observed in the wind tunnel.

## Program Objective

The basic objective of this project is to evaluate, by both wind tunnel and full scale testing, the prospects of substantially improving the aerodynamics, and hence fuel economy, of typical operational buses. The emphasis is on drag reduction though use of add-on type devices and minor vehicle recontouring which could practically and economically be incorporated or retrofitted to the existing fleets of commercial carriers. In consequence, the project has used as specific examples the Motor Coach Industries MC-7 and MC-8 vehicles as the standard baseline configurations for drag reduction device evaluation.

## Basic Configuration Description

The MC-7 and newer MC-8 buses are in widespread use with Greyhound. The overall configurations are shown in Figure 1. The general characteristics of these vehicles are:

| | MC-7 | MC-8 |
|---|---|---|
| Passenger capacity | 46 - 49 | 46 - 49 |
| Length | 40' | 40' |
| Width | 8'-6" | 8'-6" |
| Height | 10'-6" | 10'-6" |
| Weight (Gross) | 36,000 | 36,000 |
| Power | 290 hp | 290 hp |

Both configurations are similar in overall shape, each being limited in width and length (but not height) by appropriate government (ICC)

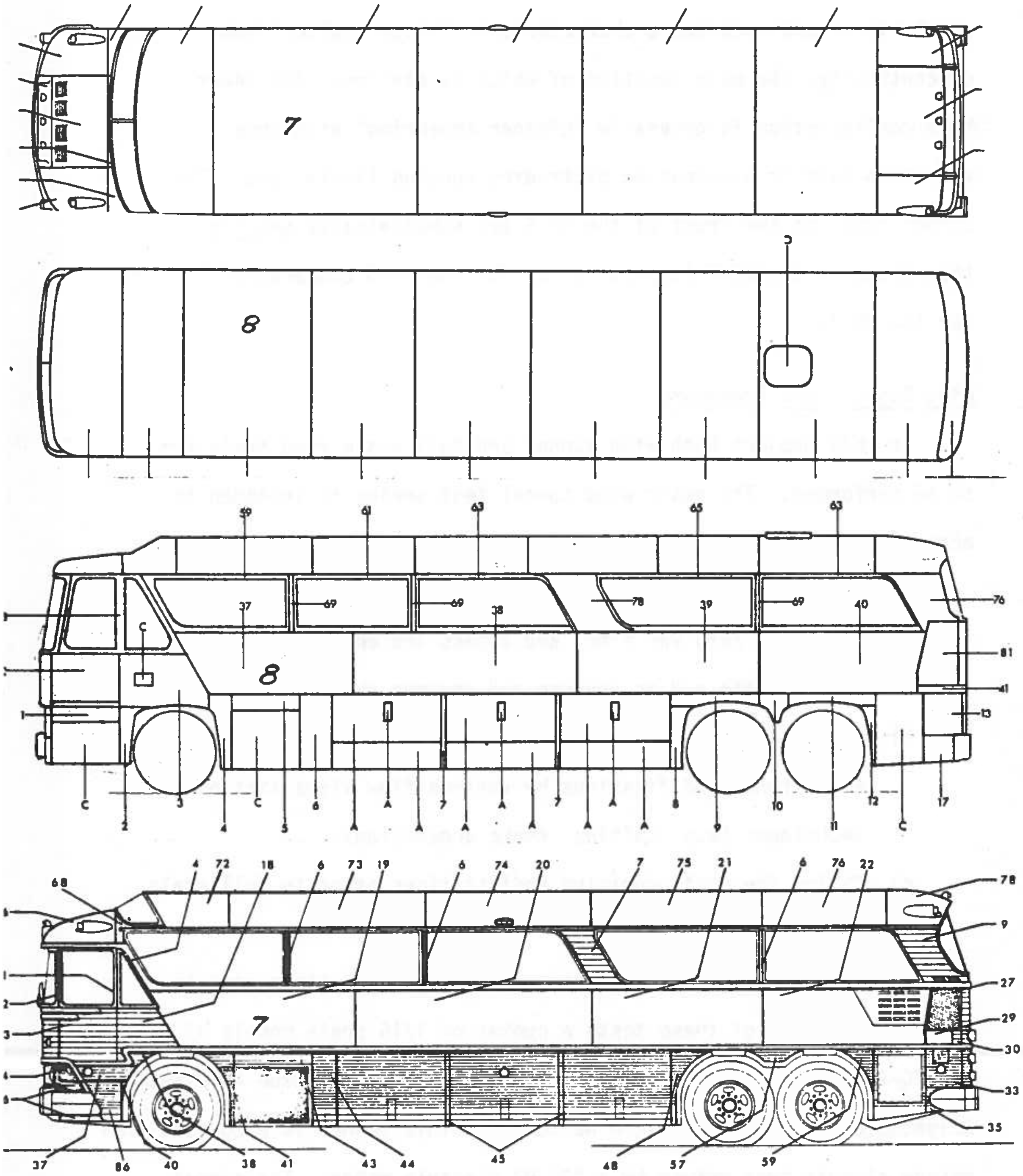


Figure 1. Basic Configurations

regulations, and each has a characteristic "vista cruiser" hump discontinuity, the main function of which is styling. The newer MC-8 configuration is generally "cleaner appearing" with some attention paid to eliminating protruding running lights, etc. The corner radii on the front of the MC-8 are substantially <u>smaller</u> than those on the MC-7 (typically 8" for the MC-8 compared to 12" for the MC-7).

<u>Wind Tunnel Test Procedure</u>

In this project both wind tunnel and full scale road tests are to be performed. The basic wind tunnel test series is intended to accomplish the following:

a) Evaluate the drag of the baseline configurations in tailored yaw and zero yaw flow, and assess the aerodynamic benefits of candidate add-on devices and contour changes.
b) Evaluate the general flow field around the vehicles with and without modifications by various flow visualization techniques (e.g. tufting, smoke generation).
c) Tailor the most promising modifications prior to full scale fabrication and testing.
d) Provided data for comparison with data from other sources.

For purposes of these tests a number of 1/16 scale models of the MC-7 have been cast from plaster for test in the Purdue Aerospace Sciences Laboratory subsonic wind tunnel. This tunnel is a conventional return circuit type driven by a 400 HP electric motor. The tunnel closed throat test section is 3' high by 4 1/2' wide by 5' long with a maximum speed capability of 300 mph. The test section is fitted with an Aerolab Supply Co. six-compound balance system with motorized pitch and yaw control.

The models are mounted on a single bayonet through the approximate center of gravity of the full scale bus. All tests have been run at a constant tunnel speed of 90 mph giving a test Reynolds number (based on hydraulic diameter) of $5 \times 10^5$. Ground influence is simulated by a short stationary ground plane approximately twice the length of the model and spanning the test section. This ground plane removes the influence of tunnel wall boundary layer build-up. This arrangement is shown in Figure 2 which includes MC-7 and MC-8 baseline test installations.

## Basic Configuration Testing

Prior to evaluation of any modifications, the basic MC-7 configuration and the overall test set-up were investigated. These tests involved assessing the following factors:

a) Ground plane misalignment

b) Drag increments due to wheels

c) Height of model above ground plane

d) Variation in zero yaw drag with speed and thus Reynolds Number

Next, in order to assess the basic drag characteristics of a general bus shaped, bluff body vehicle and to provide data for comparison with wind tunnel tests from other sources, the basic MC-7 model was fitted with rectangular, sharp cornered pine blocks, so that the front end assumed a pure rectangular shape. These blocks were then systematically contoured with increasing corner radii, first on the sides alone, then the top alone and finally in combination. The configuration

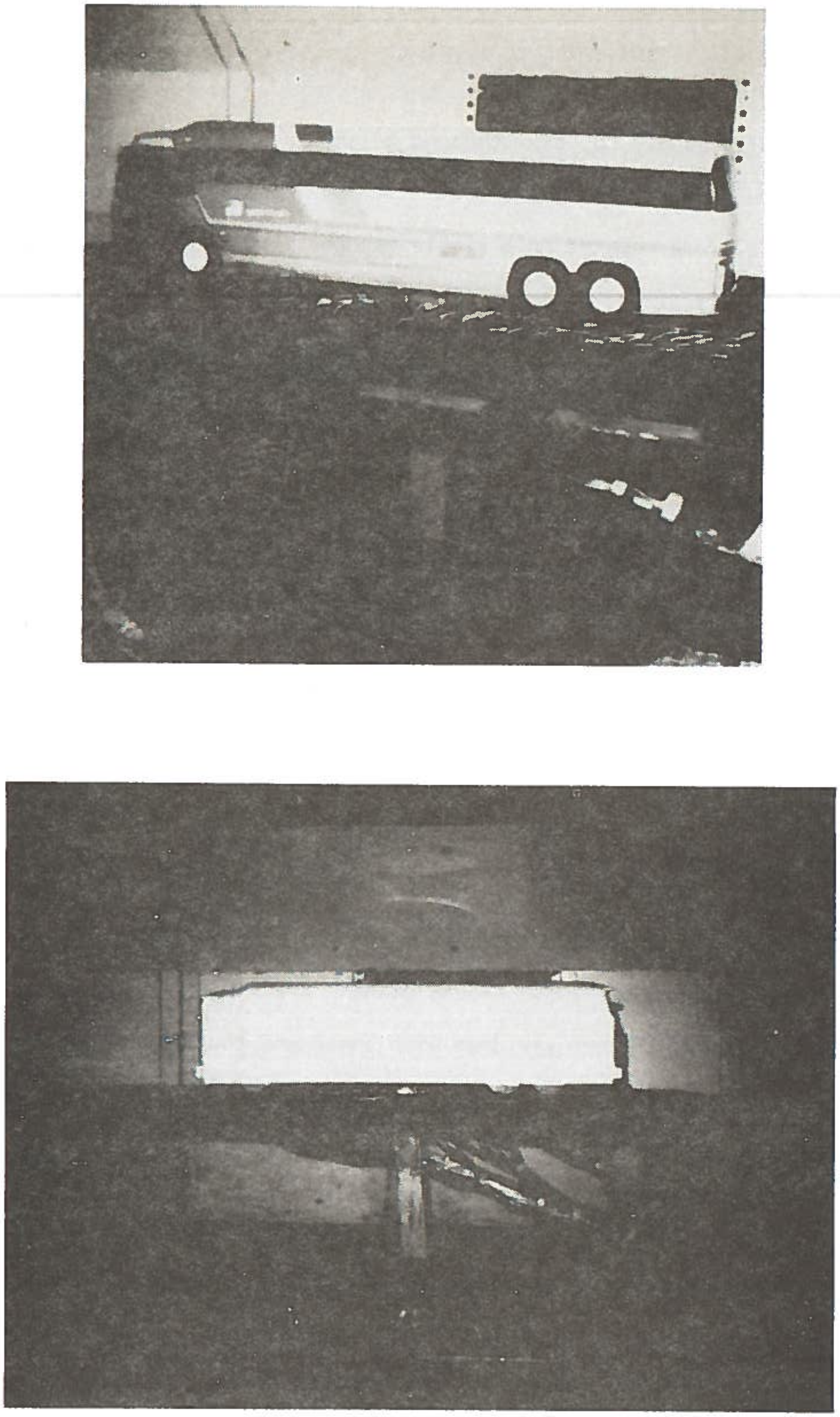


Figure 2. Baseline Test Installations

and some typical results are shown in Figure 3. As anticipated, from test results previously reported, increasing corner radius showed an initially large decrease in drag coefficient, with change increments decreasing as a full hemispherical nose shape is approached. The tests confirm the fact that front corner radius has a strong effect on drag, the major drag build-up is on the front end of the bus and the MC-8 with its sharper front corner radii has a higher drag than the MC-7; despite the fact that the MC-8 has a generally "cleaner" appearance.

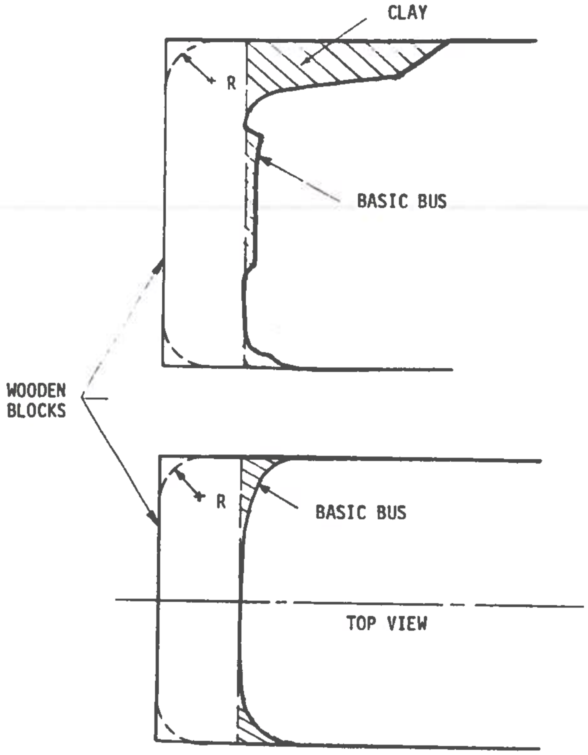
## Wind Tunnel Tests of Add-On Devices

The basic goal of these tests has been to evaluate as many types of device as possible which could be simply and economically retrofitted to existing vehicles and/or investigate the influence of simply achieved minor (i.e. requiring no alteration of major structural members) contour modifications; rejecting any that gave less than 8 - 10% reduction in drag.

The general types of add-on devices tested to date are shown in Figure 4. The results of these tests on the MC-7 may be summarized as follows:

Rear End Add-ons:

1. Splitter plates - negligible effect with any size plate.
2. T-Shaped plates - negligible effect.
3. Beaver tail - negligible effect with any practical configuration.
4. Sting/Disc - 3% drag reduction in best case. General drag increase.
5. Turning Vanes - negligible effect.



| | $C_D$ | % Change |
|---|---|---|
| Original Configuration | 0.630 | - |
| Square Front (Block) | 0.663 | +5 |
| 18" side radius only | 0.353 | -44 |
| 18" roof radius only | 0.513 | -30 |
| 24" roof rad., 18" side rad. | 0.273 | -57 |
| 24" roof & bottom rad., 18" side | 0.271 | -57 |

Figure 3. Basic Bus Shape Tests

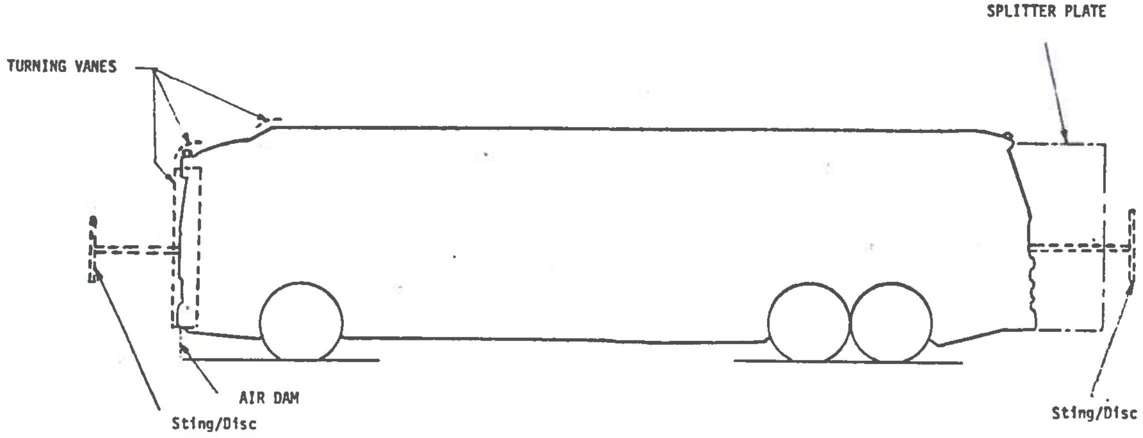


Figure 4. Add-On Devices

Front End Add-ons:

1. Front mounted sting/disc - slight drag increase in all configurations.
2. Turning vanes (a. Sides, b. Front roof, c. Hump) - less than 3% drag reduction in best case (single vane above windshield).
3. Air dam (below bumper) - slight drag increase.

Other Add-ons:

1. Wheel wells faired - negligible effect

## Front End Contour Changes

The generally very disappointing results obtained with simple add-on devices together with results from concurrent flow visualization tests indicated that the major drag sources on the MC-7 in zero-yaw flow were in the areas of the bumper and the front roof from the sharp lip above the windshield to the top of the roof hump. Thus a variety of roof and bumper fairings were tested, using modeling clay to achieve minor contour variations. To date the simple hump fairing shown in Figure 5 has given the best results, with a net drag reduction of 22%. When this fairing is installed there appears to be no further advantage in fairing the bumper.

The shell type fairing shown in Figure 5 accomplishes the following:

a) It provides a large radius smooth contour at the front end of the roof line where it joins the windshield.

b) It smoothly fairs out the roof hump which was identified as a major source of flow disruption and drag.

c) It appears to confine the large stagnation region observed on the front face of the bus creating in effect a bubble of stagnant air around which the in-coming free stream air flows more favorably.

In consequence of the good results obtained with the roof fairing, a substantial amount of recent effort has gone into tailoring and refining the basic shape, and preparing templates for fabrication of a full scale shell for road testing.

Work is presently in progress to evaluate the influence of more radical alteration of the upper visor contour, to eliminate the sharp visor lip entirely and fair out the hump. Such a modification, in practice, would require a new forward roof panel but would not affect any major structural (load carrying) member of the bus.

## Full Scale Testing

The overall plan and procedures for the full scale test portion of the project are presently being formulated. Basically the tests will involve monitoring fuel consumption on buses with and without modification during runs of substantial length at typical cruise speed on local sections of Interstate Highway.

A second series of full scale tests involves flow visualization through extensive tufting of examples of both the MC-7 and MC-8. The MC-7 portion has been completed and sample results are shown in the photographs in Figure 6. These tests strongly verify the results previously obtained in the wind tunnel.

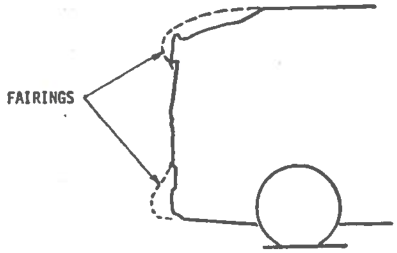


Figure 5. Simple Hump Fairing

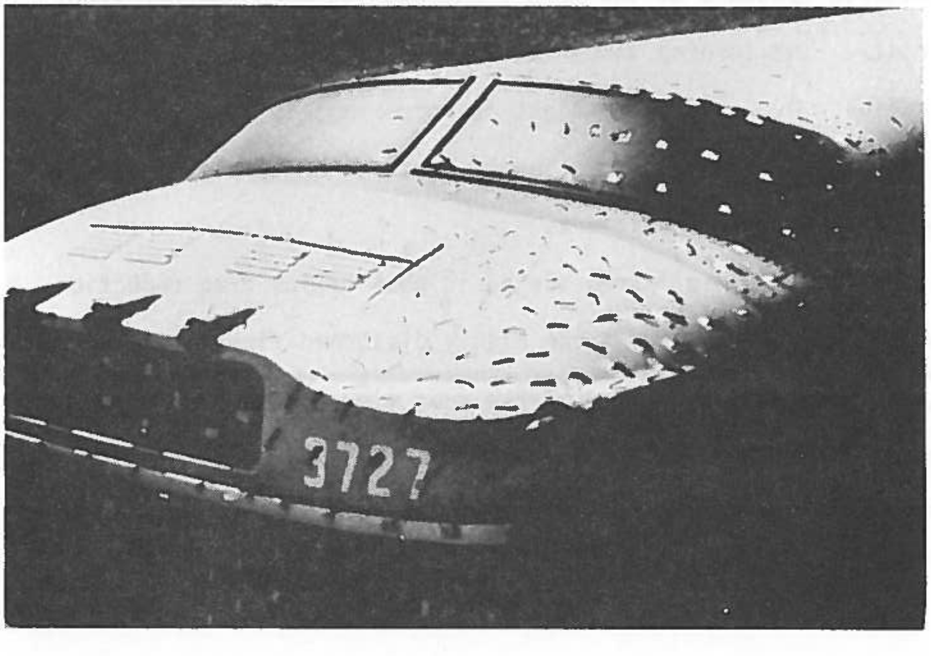


Figure 6. Flow Visualization Testing

## Future Activities

The major immediate goal of the project is to proceed with the full scale testing of the MC-7 modifications, beginning with fabrication of the roof fairing previously described. Concurrent with this work is continuation of work on the MC-8, beginning with abbreviated wind tunnel testing. Experience gained in the MC-7 wind tunnel tests, together with full scale tuft tests of an MC-8, should greatly expedite these later tests. Difficulties in obtaining suitable 1/16 scale models of the MC-8 is the primary cause of delays in these tests. At present, it appears that a roof top fairing similar to that proposed for the MC-7 and possible use of front side mounted turning vanes is the most promising approach to MC-8 drag reduction. While showing poor results on the MC-7, turning vanes may be more satisfactory on the MC-8 because of the generally cleaner, less cluttered contours of the MC-8 front end its much sharper front corner radii. The turning vanes may aerodynamically alter this corner radius. Overall, the project is approximately four weeks behind the originally proposed schedule, but can be completed within the original cost of the contract.

An important spin-off from the basic goal of bus drag reduction has been the identification of the highly disturbed flow field in the vicinity of the reflecting side of the rear view mirrors. This has been dramatically demonstrated in the full scale MC-7 tuft tests. Communications with Greyhound indicates this is a major safety problem because of build up of dirt and slush on the mirror during even mildly inclement weather operations. It appears possible, within the time scale and cost of the existing contract to test possible mirror modifications which may alleviate this problem. The drag reduction benefits of mirror streamlining, for example, will probably be minimal however.

# VALIDATING AUTOMOBILE DRIVETRAIN MODIFICATIONS THAT IMPROVE FUEL ECONOMY

Primary Investigator - Donald A. Hurter
Arthur D. Little, Inc.

## ABSTRACT

The Program Objective is to validate projected improvements in fuel economy resulting from certain automobile drivetrain modifications without compromising exhaust emissions, driveability, acceleration performance and engine life. Modifications should be representative of adaptions which could be introduced on a mass production basis by 1980.

The Scope of the Program includes:

- Review and document existing data on automobile drivetrains and design process.
- Develop modification plan, obtain hardware and modify four vehicles which are representative of a range of engine size and vehicle roominess.
- Each car is equipped with automatic transmission operating with either a wide range 3-speed or 4-speed and torque converter lock-ups. Test cars use urban and highway Federal test procedures, SAE J 1082 fuel economy, driveability and performance tests.

A four speed and a wide range three speed transmission, both with lock-up torque converters are being prepared based on a Chrysler A-727 transmission and a Laycock J-type overdrive. These modifications will be tested in a 318 CID and a 225 CID 1975 Plymouth Valiant weighing approximately 3200 lbs. A four speed and wide range three speed transmission, both with lock-up torque converter, will be prepared based on a Chrysler A-904 transmission and a J-type Laycock overdrive. These modifications will be tested in a 2000 cc and a 1600 cc 1975 Dodge Colt weighing approximately 2250 lbs.

Cars will be tested to validate predicted computer simulations of fuel economy for various lock-up torque converter modes.

Analysis will be made to determine impact on exhaust emissions, driveability, acceleration, and power train life.

## PURPOSE OF THE STUDY IS:

- To Validate the Potential of Improved Fuel Economy by Improving the Matching of Engine Operation to Road Load
- To Establish the Impact of Transmission Modifications on Exhaust Emissions, Driveability, Acceleration and Engine Life
- Compare the Test Results with Computer Simulation Predictions

| Modification | Fuel Economy Improvement % |
|---|---|
| Lock-up Torque Converter in 2 & 3 Speed (Conventional Automatic) | 5–6 |
| Wide Range 3 or 4 Speed (No Lock-up) | 7–10 |
| Combination of Lock-up and Wide Range | 12–16 |

- Describe the Technical Design Decision Process to Show How the Transmission Designer Matches Vehicle Requirements with Engine Characteristics for Desired Operation

## PARTICIPANTS IN THE PROGRAM

Arthur D. Little, Inc. – Principal Investigators and Vehicle Modifier

B&M Automotive Products Co. – Prototype Transmission Hardware

Olson Laboratories Inc. – Testing

Eaton Corp – Test Track Facilities

Consultants – Max M. Roensch
Milton H. Scheiter
Frederick Hooven
Program Review – Walter R. Laster – Borg-Warner Corp.

## CONDITIONS OF THE STUDY

### TRANSMISSION SHOULD BE:

- Automatic
- Representative of Present State of the Art
- Capable of Mass Production by 1980's with Minor Facility Disruption
- Capable of Torque Converter Lock-up in All But First Gear at Command or Automatically
- Both Wide Range 3-Speed and 4-Speed Gear Box

### VEHICLES SHOULD BE:

- Representative of 1975 Compact- and Sub-Compact-Size Vehicles
- Engine Sizes to Range from Approximately 90 CID to 320 CID

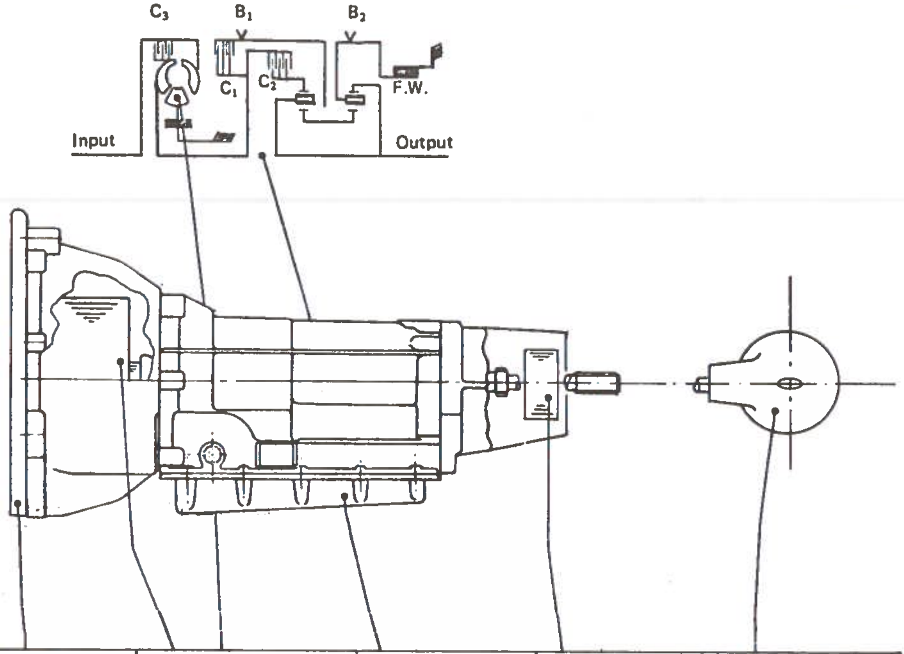
### TESTS SHOULD CONSIST OF:

- Federal Test Procedure – Urban and Highway
- SAE J 1082 Fuel Economy
- Driveability Evaluation
- W.O.T. Acceleration Velocity and Distance

REFERENCE

| Car Number | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Make | Plymouth | | Dodge | |
| Model Name | Valiant | | Colt | |
| Body Type | 4-Door Sedan | | 2-Door Sedan | |
| Wheelbase | 111" | | 95.3" | |
| Curb Weight | 3200# | | 2250# | |
| Engine Type | OHV–8 | 6 Inline | 4 Inline | 4 Inline |
| Displacement | 318 CID | 225 CID | 122 CID | 97 CID |
| | 5213 CC | 3688 CC | 2000 CC | 1600 CC |
| Horsepower | 145–4000 | 95–3600 | 89–5200 | 79–5200 |
| Unmodified Transmission | A727 Torque Flite | | A904 Torque Flite | |
| 1st Gear | 2.45:1 | | 2.45:1 | |
| 2 | 1.45:1 | | 1.45:1 | |
| 3 | 1.00:1 | | 1.00:1 | |
| Standard Axle Ratio | 2.45 | 2.76 | 3.55 | 3.89 |

## SCHEMATIC OF WIDE RANGE 3 OR 4 SPEED MODIFIED DRIVE TRAIN



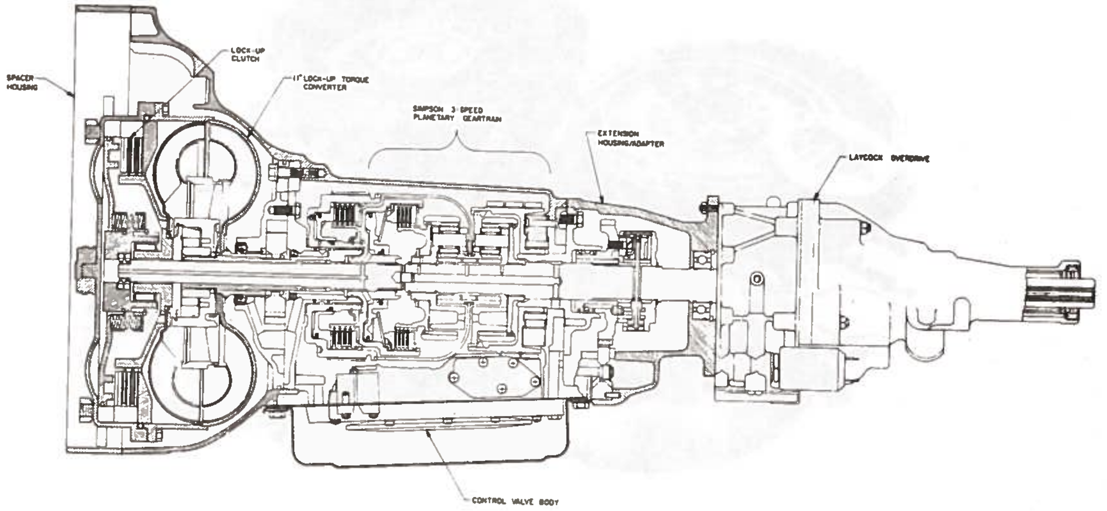
| Bell Housing Adapter for 225, 318, 122 and 97 CID Engines | Torque Converter with Lock-up in Any Mode or Not at All with Separate Manual or Automatic Control | Torque Flite A727 or A904 3-Speed Transmission | J-Type Laycock Overdrive with Electric Shift Control Signalled Automatically From Gear Box or Manually by Driver | No Axle Ratio Change from Base Car Modified Drive Shaft Length and, If Necessary, Torsional Damper Added |
|---|---|---|---|---|

3 or 4 Speed
For All Vehicles

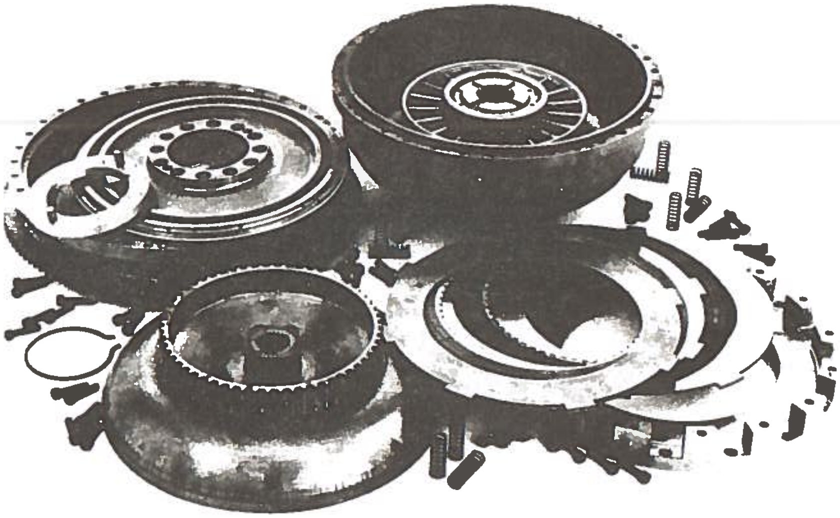
## DRIVE TRAIN MODIFICATIONS

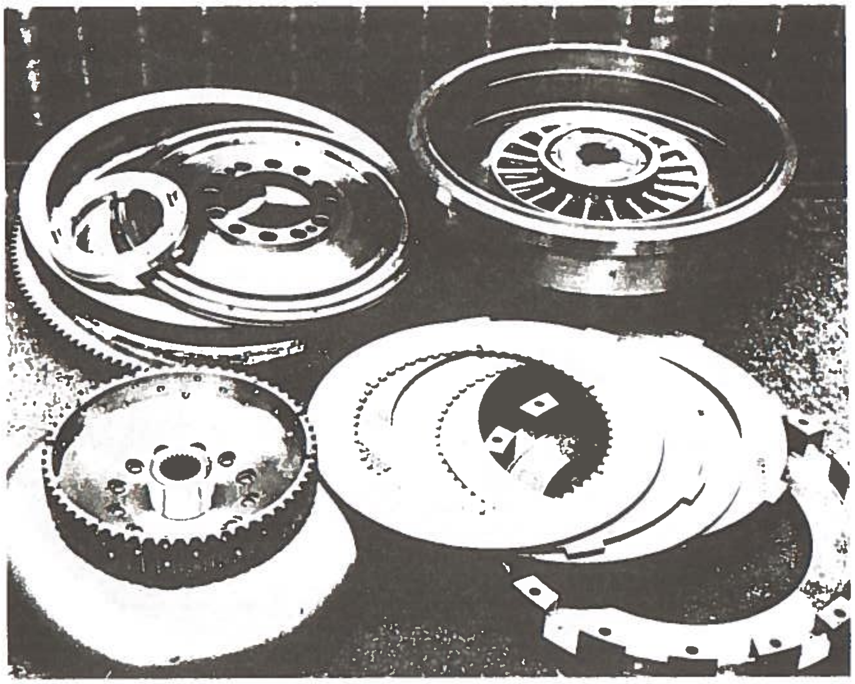
| | Standard 3 Speed | Wide Range 3 Speed | | Wide Range 4 Speed |
|---|---|---|---|---|
| Lock-up Converter | None | 2,3 Or Not At All | | 2,3,4 Or Not At All |
| Gear Ratio | | | Optional 2nd Mode | |
| 1st | 2.45:1 | 2.45:1 | 2.45:1 | 2.45:1 |
| 2nd | 1.45:1 | 1.45:1 | 1.13:1 | 1.45:1 |
| 3rd | 1.00:1 | .778:1 | .778:1 | 1.00:1 |
| 4th | – | – | – | .778:1 |
| Ratio Range Increase | 1.00 | 1.28 | | 1.28 |

## TRANSMISSION MODIFICATION TO STANDARD AUTOMATIC



## MODIFIED TORQUE CONVERTER





## SUMMARY OF TEST PROGRAM
## FOR EACH VEHICLE AND EACH CONDITION

| Test Description | Baseline Standard Vehicles | Modified Wide-Range Vehicles 3 Speed | Modified Wide-Range Vehicles 4 Speed |
|---|---|---|---|
| | | No Lock-up, Lock-up 3,2 | No Lock-up, Lock-up 4,3 |
| Federal Test Procedure | | | |
| Dynamometer Test | | | |
| E.P.A. Urban | 3 | 3 | 3 |
| E.P.A. Highway | 3 | 3 | 3 |
| SAE J 1082 Fuel Economy | | | |
| Road Test Procedure | | | |
| Urban | 2 | 2 | 2 |
| Suburban | 2 | 2 | 2 |
| Interstate 55 MPH | 2 | 2 | 2 |
| Driveability | 2 | 2 | 2 |
| W.O.T. Velocity and | | | |
| Distance – From: | | | |
| 0 MPH for 30 Sec | 2 | 2 | 2 |
| 25 MPH for 30 Sec | 2 | 2 | 2 |
| 50 MPH for 30 Sec | 2 | 2 | 2 |
| Total for Each Vehicle | | | |
| 140 | 20 | 60 | 60 |

ANTICIPATED PROBLEM AREAS:

- Effect on Emissions of Lower Engine Speeds and Higher Loading
- Shift Feel When in Lock-up Mode
- Reaction of Engaging or Disengaging Lock-up
- Gap in Gear Ratio 2nd to 3rd in Wide-Range or 1st to 2nd 3-Speed
- Engine/Transmission Harmonic Vibrations and Damping Requirements for Drive Line
- Being Able to Measure Slight Changes in Fuel Economy Resulting from Different Transmission Operational Modes
- Driveability of 4-Cylinder Cars When Torque Converter is Locked Up

# AUTOMOTIVE POWERPLANT EVALUATION

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Bartlesville Energy Research Center
U.S. Energy Research & Development Administration
Bartlesville, Oklahoma

## ABSTRACT

The objective of this program is to obtain automotive engine performance data for use in estimating vehicle emission and fuel economy in varied service and duty.

An experimental test procedure for generating fuel consumption and emissions data adequate to characterize an engine over its full operating range has been developed for steady-state tests. The development of a test procedure for transient testing is currently underway.

The steady-state data will be collected from approximately 23 different engines, including:

16 current production spark-ignition engines,
3 pre-production or prototype advanced design spark-ignition engines, and
4 light-duty diesel engines which are, or could be, used in passenger car applications.

To date, steady-state "engine maps" have been completed on 10 engines. A simplified model used to compare steady-state data with chassis dynamometer data indicates that results thus far can be used to obtain estimates of fuel economy in automobiles.

# INTRODUCTION

The objective of the automotive powerplant evaluation program is to obtain engine performance data for use in estimating emissions and fuel economy in varied service and duty. The performance data obtained from an engine will be referred to as an "engine map." This map provides basic engine characteristic data appropriate for use as input for engineering calculations in systems analysis involving vehicular transportation.

The specific program elements are:

1. Development and validation of test procedure.
2. Acquisition of engine performance data for three classes of engines.
3. Following and reporting developments toward an alternative fuel technology.

The current program involves developing engine maps for approximately 23 different engines. Of these, 16 are current-model, standard-production, spark-ignition engines; three are pre-production or prototype spark-ignition engines; and four are light-duty diesels which are, or could be used as automotive powerplants. These engines are listed in table 1. This sampling of engines represents a significant portion of the engine types marketed in current-model vehicles.

Except for variations noted below, each of the engines we have tested, or will test, are "fully equipped engines"* dressed with components as furnished in vehicles marketed in the 49 states outside California. The variations are:

1. An equivalent heat exchanger is used in place of the radiator.
2. The alternator or generator is not used unless it is required to drive accessories.
3. Exhaust system configuration varies slightly from the vehicle installation, but equivalent flow restriction is provided.

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*SAE definition.

TABLE 1. - ENGINE DESCRIPTIONS

| Manufacturer | Displacement, cu in | Carburetor, (barrels/fuel inj.) | No. of cylinders |
|---|---|---|---|
| STANDARD-PRODUCTION, SPARK-IGNITION ENGINES | | | |
| * AMC | 258 | 1 | 6 |
| Buick | 455 | 4 | 8 |
| * Chevrolet | 350 | 4 | 8 |
| * Chevrolet | 350 | 2 | 8 |
| Chevrolet | 250 | 1 | 6 |
| * Chevrolet | 140 | 2 | 4 |
| Chrysler | 318 | 2 | 8 |
| Chrsyler | 225 | 1 | 6 |
| * Datsun | 119 | 2 | 4 |
| Ford | 400 | 2 | 8 |
| Ford | 351 | 2 | 8 |
| Ford | 250 | 1 | 6 |
| Ford | 140 | 2 | 4 |
| Mazda | 70 | 4 | 2 rotors |
| Saab | 121 | FI | 4 |
| Volvo | 121 | FI | 4 |
| PRE-PRODUCTION OR PROTOTYPE ENGINES | | | |
| Chevrolet | 350 | Dresserator | 8 |
| Chevrolet | 350 | 4 bbl, turbocharged | 8 |
| * Honda | 91 | 3-CVCC | 4 |
| DIESEL ENGINES | | | |
| * Chrysler-Nissan | 198 | FI | 6 |
| * Mercedes-Benz | 183 | FI | 5 |
| * Mitsubishi | 331 | FI | 6 |
| * Perkins | 247 | FI | 6 |

*Steady-state testing completed as of November 1, 1975.

4. No fan is used.
5. Engine and emission control components are typically those supplied on engines with automatic transmissions.

Any other specific deviations are noted in the respective engine report.

## STEADY-STATE ENGINE TEST PROCEDURE

The first task in the engine characterization program was to develop a test procedure through which repeatable, representative steady-state engine data could be obtained. For this purpose an engine equipped as noted above was installed on a test stand and run through a break-in schedule designed to simulate approximately 1,500 vehicle miles.

After engine break-in, experimental work was begun taking data at each one of an array of points, selected to represent nine distributed loads at each of seven engine speeds. Engine loads are computed as a percentage of maximum power at the respective engine speed.

The original set of data points to be run on an engine then consists of 60 to 70 speed/load points representing the engine's entire operating range from idle, no load, to maximum or rated power. About half of these points are re-run to show that the test results are repeatable and that general trends in the data are representative.

A variety of parameters and conditions are measured; those of primary interest are fuel consumption, rpm, torque, and exhaust emissions.

Emission measurement is as follows:

--Carbon monoxide (CO) and carbon dioxide ($CO_2$) by non-dispersive infrared analysis

--Unburned hydrocarbon by heated flame ionization detector

--Oxides of nitrogen ($NO_x$) by chemiluminescence detector

--Oxygen by polarographic technique

--Smoke by in-line opacity measurement

--Sulphate by barium chloranilate procedure

Other measurements of interest are listed in tables 2 and 3 for gasoline and diesel engines, respectively.

## TRANSIENT ENGINE TEST PROCEDURE

Experimental work in development of the transient test procedure was begun in late summer. The procedure thus far involves an engine test setup as described above with the addition of an inertial loading system and a constant volume sampler (CVS) system for acquisition of exhaust sample.

The inertial system is designed to provide the engine loading effects of a specific weight vehicle as these effects are manifested through discrete ramp accelerations or decelerations of a short duration. Mass emission rates and fuel consumption will be determined from CVS samples. These data will be used in predicting emissions and fuel rates over engine transients as would be encountered in whichever cycle is to be estimated.

Using the results of the transient tests and the data from steady-state engine maps a third test procedure will be designed. This will in effect describe the amount of testing which is necessary to define an engine's operating characteristics in detail that is adequate to enable acceptable close estimation of engine performance in actual service over any reasonable duty cycle.

## SIMPLIFIED MODEL FOR FUEL ECONOMY ESTIMATES

A specified driving cycle for vehicle testing can be thought of as being comprised of two engine modes--"powered" and "non-powered." Knowledge of the particular cycle reveals the duration of each mode. The powered mode for a given vehicle weight implies both an average and peak horsepower requirement. Using the idle fuel consumption rate for "non-powered" operation, and the fact that the "powered" fuel consumption rate may approximate a linear function of speed and

## TABLE 2. - SPARK-IGNITION ENGINE TEST MEASUREMENTS

- Barometric pressure
- Humidity
- Inlet air temperature
- Engine speed, rpm
- Torque, ft/lb
- Fuel rate
- Throttle position
- Ignition timing
- Manifold vacuum

- Oil temperature
- Coolant temperature
- Exhaust temperature*
- Exhaust pressure*
- Oil pressure

- CO concentration*
- $CO_2$ concentration*
- $O_2$ concentration*
- Unburned HC concentration*
- $NO_x$ concentration*

* When a catalytic converter is used in the exhaust systems these parameters are monitored before and after catalyst.

$SO_3$ concentration is measured on certain engines in select modes.

## TABLE 3. - DIESEL ENGINE TEST MEASUREMENTS

- Barometric pressure
- Humidity
- Inlet air temperature
- Engine speed
- Torque
- Fuel rate
- Control lever position
- Combustion air flow rate
- Inlet air restriction

- Oil temperatue
- Coolant temperature
- Exhaust temperature
- Oil pressure
- Exhaust pressure

- Exhaust opacity
- CO concentration
- $CO_2$ concentration
- $NO_x$ concentration
- Unburned HC concentration

$SO_3$ concentration is measured on certain engines in select modes.

torque for low to moderate engine speeds, an estimate of the cycle fuel economy can be obtained from steady-state engine test data.

A comparison of fuel economy estimates for engines (those with completed steady-state engine maps) at various vehicle weights with published vehicle fuel economy data is given in table 4. The agreement is considered to be quite good, in all cases except for the AMC. However, the results from chassis dynamometer tests performed at the Bartlesville Energy Research Center on this vehicle support the estimated fuel economy.

## CYCLE SIMULATION FROM ENGINE MAPS

The engine map data can be used as input to computer simulations of vehicle test cycles. In doing this, we understand that the Transportation Systems Center people have found fuel economy and acceleration performance are predictable to within 5 to 10 pct. Predicted $NO_x$ emissions are accurate to within about 25 pct. Predicted carbon monoxide and unburned hydrocarbon emissions are consistently overpredicted and underpredicted, respectively. The actual data used in the comparison came from Environmental Protection Agency chassis dynamometer tests.

## ALTERNATIVE FUEL TECHNOLOGY

The final program element deals with developments toward an alternative fuel technology. This does not include any experimental work within this specific program, but is directed toward surveillance of developments in the use of alternative fuels in transport applications. Information on engine performance with alternative fuels will be summarized and updated periodically. The source of this information is to be both from industry and from results of experimental work done at the Bartlesville Energy Research Center, in its in-house research and in cooperation with other governmental agencies.

## SUMMATION

Steady-state engine tests have been completed on 10 engines including at least one engine from each category. A transient test procedure is being developed. Results from these tests do allow reasonable accuracy in predicting fuel economy.

Engine procurement is virtually complete. Four engines have yet to be delivered but are expected soon.

Future work plans include continuing steady-state engine mapping, developing transient engine test procedure, and mapping transient engine test modes.

TABLE 4.- COMPARISON OF ESTIMATED FUEL ECONOMY

| Engine / I.W., lb.. | Fuel economy, mpg | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Estimated fuel economy | | | | | | Published EPA fuel economy data | | |
| | Urban | Highway | Urban | Highway | Urban | Highway | | | |
| | 2,000 | | 3,000 | | 4,000 | | Urban | Highway | I.W., lb |
| Honda 91-CID | 27 | 39 | 24 | 35 | 21 | 32 | 27 | 39 | 2,000 |
| Chevrolet 140-CID | 32 | 32 | 20 | 30 | 18 | 28 | 21 | 29 | 2,750 |
| Datsun 119-CID | 24 | 35 | 21 | 32 | 19 | 30 | 22 | 33 | 3,000 |
| AMC 258-CID | 15 | 24 | 14 | 21 | 13 | 20 | 21 | 30 | 3,000 |
| Chevrolet 350-CID, 2V | 13 | 19 | 12 | 18 | 11 | 17 | 14 | 19 | 4,000 |
| Chevrolet 350-CID, 4V | 12 | 18 | 11 | 17 | 11 | 17 | 13 | 20 | 4,000 |
| Nissan 198-CID | 22 | 31 | 19 | 29 | 17 | 27 | - | - | - |
| Mitsubishi 331-CID | 17 | 25 | 16 | 24 | 14 | 22 | - | - | - |

# THE EFFECT OF VARIATIONS IN EMISSION CONTROL SYSTEMS ON AUTOMOTIVE FUEL ECONOMY

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California Institute of Technology
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## ABSTRACT

The objective of this effort is to generate experimental data to support an assessment of the relationship between vehicle fuel economy and emissions. Vehicle tests, engine tests, and supporting analyses will be made to study the emissions benefits and fuel economy penalties resulting from cold start emissions devices, exhaust gas recirculation (EGR) and the secondary air injection reactor (AIR) system. Efforts will be directed toward identifying and implementing an advanced cold start emissions system and improved control strategies for the EGR and AIR systems which will show improvements in fuel economy and/or emissions over the baseline vehicle.

The presentation will give results of the baseline vehicle and engine tests and will identify some preliminary findings of the cold start emissions study. A discussion of the test and analysis activities planned for the remainder of the program will also be included.

This paper will present the current status and plans for an automotive program being done by the Jet Propulsion Laboratory for the Department of Transportation/Transportation Systems Center. Only a small fraction of the effort has been completed at this time; therefore, much of the paper will be directed to the planned activities.

The objective of the effort is to generate experimental data to support an assessment of the relationship between fuel economy and emission control systems. Data will be obtained at both the vehicle and engine levels to provide a more complete understanding of this interaction. A detailed investigation will be made for three emission control systems: cold start emissions devices, exhaust gas recirculation (EGR) systems and air injection reactor (AIR) systems. The program will provide a systematic evaluation of the interaction between fuel economy and the emission control systems which will be used to meet the more stringent Federal emissions standards. The effort has as a goal the achievement of an improved automobile engine/emissions control system configuration which will yield increased fuel economy and/or lower emissions levels when compared with the stock system.

Care was exercised in selecting a vehicle to insure that meaningful results would be obtained in this effort. The vehicle selected was a 1975 Plymouth Valiant with the 6-cylinder engine. The engine is a 225 cubic inch displacement (CID) engine with the slant-6 design. In EPA certified tests this vehicle/engine combination gave mileage in the urban driving cycle which was among the best achieved in the 3500 lb inertia weight class. By selecting a vehicle from among the best fuel economy vehicles, any positive results achieved during the program become more meaningful. A vehicle in the 3500 lb inertia weight class was chosen since lighter vehicles seem to be the pattern of the future. The vehicle also came equipped in California with the emission control systems (exhaust catalyst, EGR and AIR) which were necessary for this evaluation effort.

After a 4000 mile break-in period and tune-up to factory specifications, baseline tests of the stock vehicle were started. The program includes baseline testing of the vehicle and the engine. Chassis dynamometer testing of the stock vehicle has been completed, and engine dynamometer testing is in progress. The chassis dynamometer activity included tests over the urban and highway driving cycles. Both CVS-3 bag analysis and modal analysis of emissions were obtained for the urban cycle. Fuel economy results were obtained for both urban and highway cycles. The results of the baseline vehicle tests are given in the following table.

| | 1975 California Standard | Urban Driving Cycle* | Highway Driving Cycle* |
|---|---|---|---|
| HC, g/mi | 0.9 | 0.56 | |
| CO, g/mi | 9.0 | 3.73 | |
| $NO_x$, g/mi | 2.0 | 0.99 | |
| Fuel Economy, mpg | | 14.75 | 19.98 |
| EPA Certified Fuel Economy, mpg | | 15 | 20 |

*Results are the average of 3 tests.

Upon completion of the baseline vehicle tests, the engine was removed from the vehicle and is currently being tested on the engine dynamometer. These tests will include engine maps of brake specific fuel consumption and HC, CO and $NO_x$ emissions. Emissions maps will be made for conditions upstream and downstream of the exhaust catalyst. Equivalence ratio and spark advance characteristics will be determined for the stock carburetor and stock ignition system calibrations. Measurements of EGR and AIR flow rates will be made to determine the control strategy currently implemented on the stock vehicle. The EGR valve and the AIR pump/diverter valve assembly and their associated vacuum controls have been bench tested to establish valid calibration curves which will be used to determine flow rates.

Since for most vehicles a significant fraction of the HC and CO emissions produced during the urban driving cycle occur while the engine is still cold, improved cold start emissions devices and techniques potentially offer large payoffs in lowering emissions. Examination of the urban driving cycle results for the baseline vehicle indicate reductions of HC and CO emissions by 40 and 80 percent respectively are possible by eliminating the cold start emissions.

A study has been made of the cold start system on the baseline vehicle to gain a thorough understanding of its operation. Analyses have been performed on other current production cold start systems as well as advanced systems which have been proposed to improve cold start emissions. Based on these analytical evaluations, a modified cold start system will be selected for implementation and testing on the vehicle.

The cold start emissions problem is especially a difficult one since the system must provide effective control of HC and CO emissions only a few seconds after cranking a cold engine. The system must impose no severe driveability penalties and it must have adequate durability. This task is further complicated by the fact that some measures which are needed for $NO_x$ emissions control and good fuel economy are detrimental to HC and CO emissions control. Most of the candidate cold start approaches which have been identified can be grouped under three categories: mixture control, combustion effects and after-treatment methods. Techniques which have been considered for improving mixture control include charge preheating, atomization and vaporization, fuel injection and closed loop control of mixture ratio. In relation to the combustion process, spark retard and EGR shut-off show benefits in cold start emissions performance. After-treatment methods which have been considered include exhaust port liners, air injection, thermal reactors, start catalysts, fast warm-up of catalyst and charcoal canister. At this time, no firm selection of the modified cold start system to be implemented in this effort has been made.

A series of sensitivity tests will be made on the engine dynamometer to determine the effects of EGR flow rate and spark advance on fuel consumption and emissions. Data from these tests will be used to identify optimum EGR and spark advance schedules. A computer simulation model of the urban driving cycle will be used to establish the potential payoff from implementing an EGR control strategy different from the stock system. If an improved EGR strategy is identified, it will be installed and tested in the vehicle on the chassis dynamometer.

In a similar way sensitivity tests will be made on the engine dynamometer to determine the effects of AIR flow rate on exhaust emissions. Emissions data will be used to identify the optimum AIR control strategy. A computer simulation model of the urban driving cycle will be used to establish the potential payoff from implementing this optimum AIR strategy. If the optimum strategy yields significant improvements over the stock system, it will be installed and tested in the vehicle on the chassis dynamometer.

Utilizing the results of the EGR, AIR, and cold start emissions efforts, an improved emission control system will be implemented on the vehicle. The goal of this improved vehicle is to meet the

0.41/3.4/2.0 emission level with a 25 percent better mileage than the stock vehicle. Chassis dynamometer tests of the modified vehicle will be made over the urban and highway driving cycles and the results compared with the stock vehicle results.

# THE DEVELOPMENT OF PERFORMANCE EVALUATION CRITERIA FOR LEAN OPERATING CONVENTIONAL SPARK-IGNITION ENGINES

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## ABSTRACT

A program to develop a sound technical framework for evaluating changes in conventional spark-ignition engines to improve lean engine operating characteristics is described. The program is divided into three main tasks: I, the development of an engine combustion model; II, the performance of experiments to obtain basic information for the performance model; and III, the development of performance evaluation criteria.

The basic elements of the combustion model and the role of the combustion model in the development of the performance evaluation process are discussed. Also the relationship of the experimental investigations to the combustion model is discussed. The experimental work includes, I, the measurement of laminar flame speeds at pressures and temperatures typical of SI engine operation, II, the measurement of flame propagation rates, and III, the measurement of turbulent velocities and scales in a motored engine. A discussion is presented on the experimental techniques and apparatus involved. Some preliminary results from the combustion model which show i, the effect of the initial volume ignited on the rate of flame propagation and the ignition delay time and ii, the capability of the model to predict the rate of burning as a function of stoichiometry will be presented.

## 1.0 Introduction

There is considerable and increasing interest in lean dilute operating of conventional spark-ignition engines$^{(1)}$. Empirically it is known that improved mixture preparation and distribution, and ignition systems with higher energy and longer duration sparks can extend the lean operating limit (see for example (2)). Ultra lean engine operation without misfire has attractive emissions and fuel economy characteristics. Hydrocarbons, carbon monoxide and oxides of nitrogen emissions can all be reduced below levels typical of current emission controlled spark-ignition engines. There is little question that emission levels comparable with the 1975 California interim standards (0.9 g/mile HC, 9 g/mile CO and 2 g/mile $NO_x$) can be achieved. These emission levels could be obtained without excessive spark retard with consequent significant improvements in fuel economy. If interim standards are adopted by Congress for the next several years, as is quite likely, then the ultra lean engine approach would avoid the need for catalysts and would realize a further fuel economy gain through the use of higher octane leaded gasoline and higher engine compression ratios.

However, our understanding of the mechanism which limit the lean operation of conventional spark-ignition engines is currently inadequate. Many ideas for extending the lean operating limit have been proposed (e.g. ultrasonic fuel atomizers, sonic carburetors, extensive heat exchange between intake and exhaust manifolds, higher energy ignition systems, long duration discharge ignition systems, novel and multiple spark electrode configurations). Each of these has been tested empirically and has shown some potential for extending the lean operating limit. But no adequate framework is currently available to evaluate the effect of these different devices, each of which changes only one aspect of the engine combustion process.

It is the goal of the program described in this report to develop the framework for evaluation of lean engine concepts. The important lean engine operating parameters will be identified and the potential gains in engine fuel economy and improvements in emissions will be evaluated. The program is divided into three major tasks; i, the development of an engine combustion model, ii, the performance of engine and laboratory experiments to provide data on physical variables and to validate the combustion model, and iii, the development of performance evaluation criteria.

The following sections are intended to present on overview of the program and to describe our current status. Discussions were limited to the work planned for the first year.

## 2. Program Description

### 2.1 Engine Combustion Model Development

The work described in this section is designed to develop a basic framework with which to evaluate the performance of the engine components which make up the lean burning engine concept, namely, carburetor, intake manifold, cylinder head and piston geometry, ignition system characteristics and spark plug geometry and location. In order to accomplish this task it is necessary to determine what physical variables affect the ignition and flame propagation process and to incorporate these variables into the combustion model. A list of the important variables is given in Table 1. This list is divided into two segments referring to the problems of ignition and flame propagation respectively.

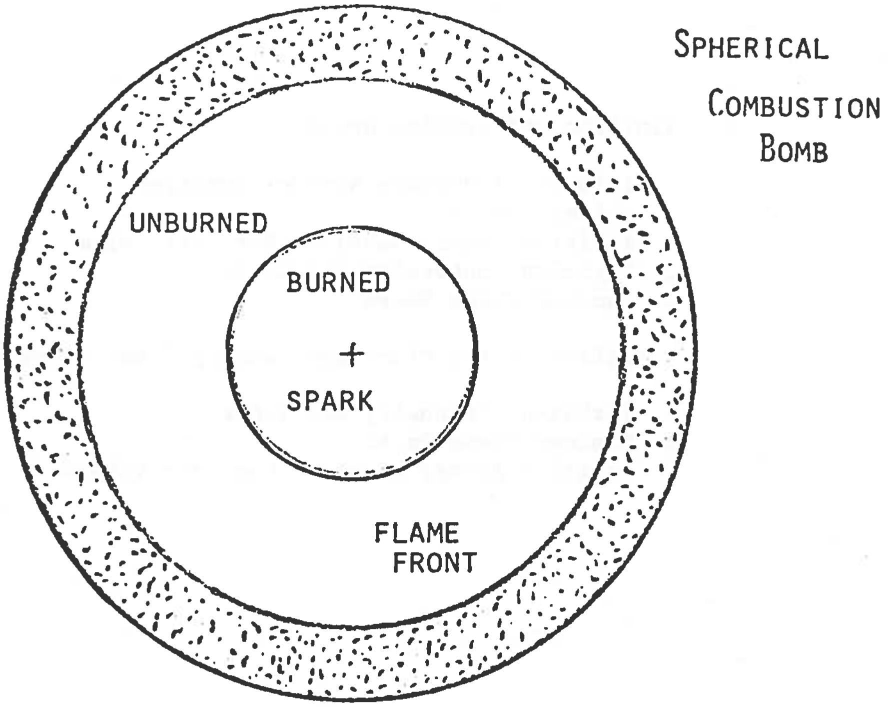
Work at MIT (3) has resulted in the development of a turbulent flame propagation model for spark-ignition engines which allows the flame initiation process, and the flame propagation process, to be examined in greater detail than has been possible to date. This model incorporates the important physical variables of turbulent

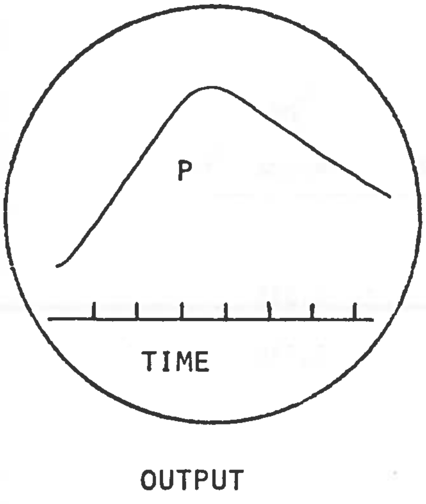
## 2.2 Laminar Flame Speed Measurements

To calculate the very important eddy burning time $\tau$ a knowledge of the laminar flame speeds at densities above atmospheric is required for both pure hydrocarbons such as isooctane and blends such as gasoline. A preliminary literature survey indicates that such data is virtually non-existent, and although various theories for predicting laminar flame speeds have been proposed they are much too uncertain to be of practical use in the present problem. Accordingly, a more extensive literature survey was performed. This survey revealed that only methane has been studies at high pressures and that no reliable data exists even for fuels such as methane.

It was decided that a spherical combustion bomb facility be constructed for measuring laminar flame speeds for practical fuels at temperatures and pressures typical of engine operation. A schematic of the combustion bomb and the typical output is shown in Figure (1). The output consists of the bomb pressure versus time. This output is then analyzed with a multi-zoned combustion model which takes into account the temperature gradients behind the flame front and which uses "real" gas properties for the calculation of the thermodynamic states. Previous investigators have used frozen specific heats in similar calculations. This is one reason for the lack of good data on laminar flame speeds. Table 2 shows the differences in frozen and equilibrium specific heats at temperatures and pressures typical of engine combustion.

LAMINAR FLAME SPEED EXPERIMENTS





<u>ANALYSIS</u>

1. LAMINAR FLAME SPEED

<u>VARIABLES</u>

1. PRESSURE
2. TEMPERATURE
3. EQUIVALENCE RATIO
4. FUEL TYPE

Figure 1. Spherical Combustion Bomb and Output

## TABLE 1. PARAMETERS THAT LIMIT LEAN OPERATION

I Ignition and Igniton Delay

- Effects of Mixture Non-Uniformities
- Volume Ignited
- Ignition Energy Supplied Per Unit Volume
- Turbulent Intensity and Scale
- Laminar Flame Speed

II Viability of the Flame and Rate of Flame Propagation

- Turbulent Intensity and Scale
- Laminar Flame Speed
- Ignition Energy Supplied Per Unit Volume

## TABLE 2. SPECIFIC HEAT DIFFERENCES

| P<br>atms | T<br>$^{o}K$ | $C_{pf}$<br>cal/gm $^{o}K$ | $C_{pe}$<br>cal/gm $^{o}K$ |
|---|---|---|---|
| 1 | 2230 | 0.360 | 0.533 |
| 10 | 3480 | 0.373 | 1.240 |

intensity, turbulent scale and laminar flame speed. A schematic of the combustion model is shown in Figure 2. It is assumed that at the time of ignition the combustion chamber is filled with turbulent eddies of size L and velocity u'. Using this information it is then possible to develop an expression for the rate of entrainment of fresh charge into the turbulent reaction zone and the characteristic reaction time.

$$\dot{m}_e = A_f \rho_u u' \qquad (1)$$

$$\tau = L / S_l \qquad (2)$$

where $\dot{m}_e$ is the rate of mass entrained, $A_f$ is the area of the flame front, u' is the entrainment velocity, $\tau$ is the characteristic burning time, L is the characteristic eddy size and $S_l$ is the laminar flame speed. Equations (1) and (2) can be used to develop expressions for rate of flame propagation and ignition delay times (3).

Although preliminary experimental tests of the model have been encouraging, further experimental verification of the model is necessary. The areas requiring further study are; i, the determination of laminar flame speeds for engine conditions and practical fuels, ii, the characterization of the turbulent field in the combustion chamber and iii, the study of flame propagation in an engine for model validation. The following sections will describe our work in these areas.

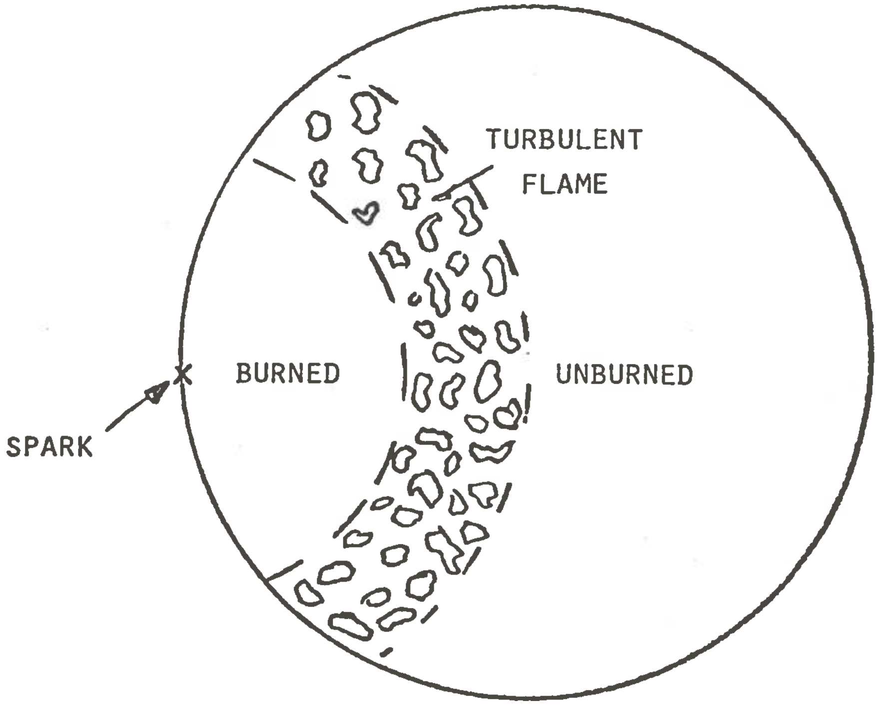


Figure 2. Combustion Model

To date we have completed our literature search, designed and constructed the spherical combustion bomb, and are presently instrumenting the facility.

### 2.3 Characterization of Engine Turbulence

There are two basic processes which must affect the character of the turbulent flow field ignited by the spark inside the engine. The first is the generation of turbulent eddies by the flow of air into the cylinder as the intake valve is opened and the piston goes down. The second is modification of the turbulent flow field ahead of the flame front during the compression stroke and combustion process. The purpose of this part of the research is to develop an overall understanding of these generation and compression processes and how they affect the turbulence in the engine at the time of ignition and during combustion. The measured turbulent intensity and eddy size from these experiments will be used as input for the turbulent combustion model as a means of model validation.

Several experiments using hot wire anemometers in motored engines have already shown that turbulent velocity fluctuations can be measured (4; 5). However, the length scales of the turbulence, and how these length scales change during the compression stroke have not been determined. We proposed to mount a commercially available hot wire in the head of the single cylinder engine. We will record, on tape, the output signals for this hot wire, and the pressure in the cylinder as a function of crank angle for motored engine operation for a range of intake manifold conditions and valve lift profiles. From these records, the turbulent intensity of the flow field and its length scales can be determined. Figure (3) shows schematically the probe arrangement and typical output to be analyzed.

Assuming the initial state of the turbulence before compression can be determined, we then want to calculate the final state as a function of the density ratio. There are related theoretical calculations in the literature which are known categorically as rapid distortion theories. We will attempt to use a modification of rapid distortion theory to correlate the observations made on an actual engine. Thus we expect to be able to predict the changes in the turbulent flow field in the unburnt mixture during the compression stroke and the combustion process. To date, we have developed the basic hot wire response equations for a turbulent flow field with high turbulent intensities and we are currently fabricating a probe to install in a single cylinder test engine

### 2.4 Flame Propagation Experiments

The single cylinder engine experimental program will be designed to provide detailed engine performance data and flame front position data to assist in model development. Experiments will be run both with gasoline as fuel, and with pure hydrocarbon fuels which are likely to have different ignition and combustion characteristics. It will also allow the testing of a variety of experimental ignition systems under closely comparable conditions to determine their effect on the lean operating limit. Not only can the effect of different electrode geometries and spark energies on the overall engine performance parameters be determined, but the effect on the turbulent flame propagation can also be determined by monitoring cylinder pressure versus time and flame front position

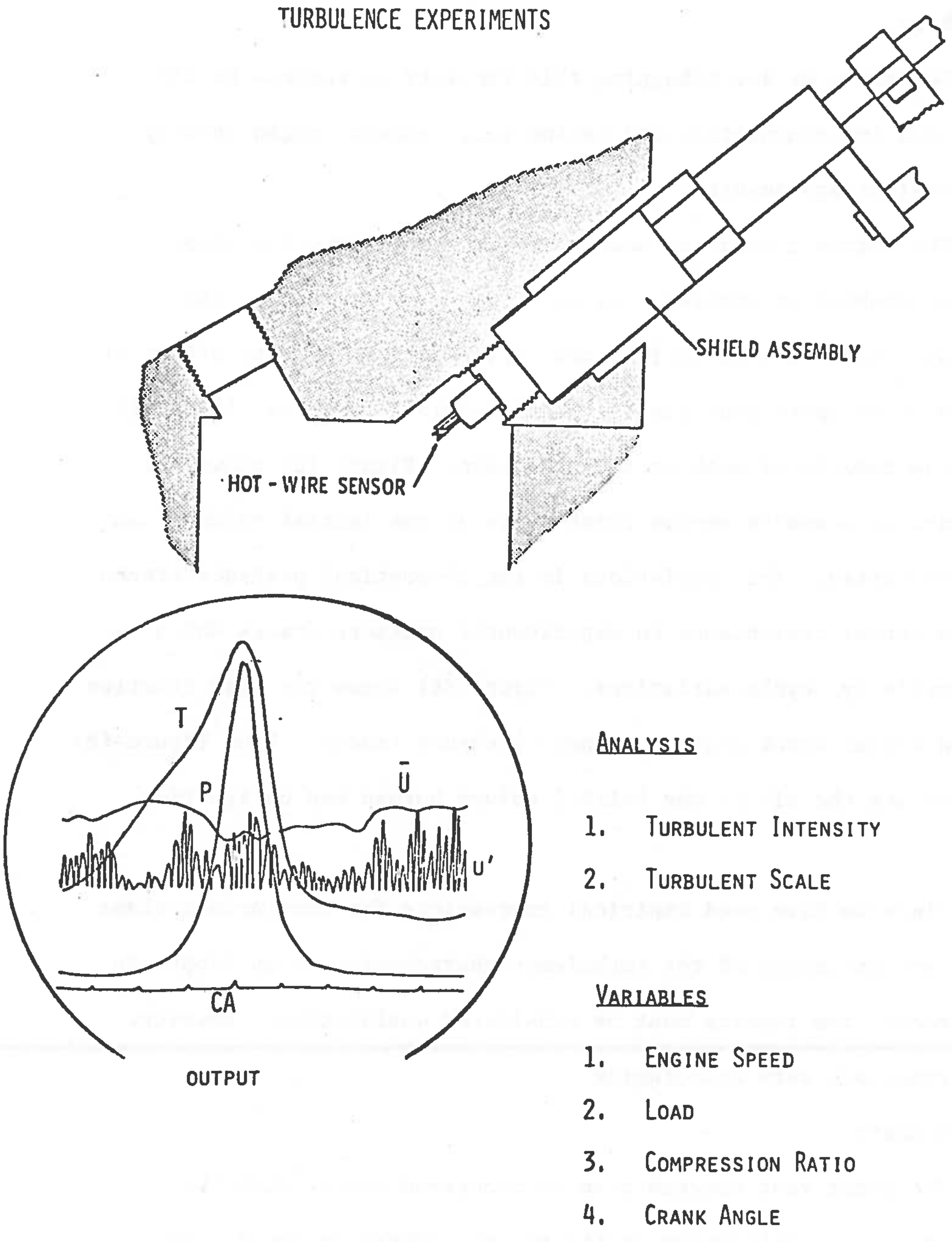


Figure 3. Probe Arrangement and Output

within the cylinder. The first year's program consists only of the flame propagation measurements. Figure (4) shows the schematic of the engine system and typical output as a function of engine variables.

Currently we are debugging this facility as regards to air leaks and instrumentation,and engine tests should begin shortly.

## 3.0 Preliminary Results

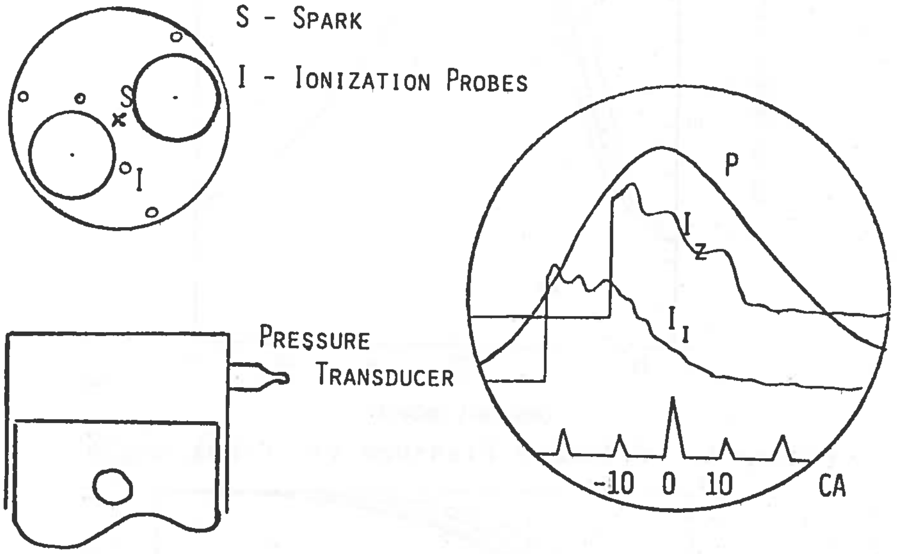
The engine combustion model has been programmed for homogeneous combustion studies. As was previously mentioned, the initial volume that is ignited can be varied to study the effect of eddy size or spark plug gap on ignition delay. Figures (5) and (6) show the results of such an investigation. Figure (5) shows the cylindrical pressure versus crank angle as the initial volume ignited varies. The variations in the theoretical pressure traces show a strong resemblance to experimental pressure traces which have cycle by cycle variations. Figure (6) shows the mass fraction burned versus crank angle for these pressure traces. From Figure (6) one can see the effect the initial volume burned has on ignition delay.

Since we have used empirical expressions for the laminar flame speed and estimates of the turbulence characteristics as inputs to this model, the results must be considered qualitative. However, the trends are very encouraging.

## 4.0 Summary

The first year program plan is concerned mainly with the development and validation of the engine combustion model. We currently have programmed the combustion model and are in the process

FLAME PROPAGATION EXPERIMENT



Engine Geometry

Output

<u>Analysis</u>

1. Combustion Duration
2. Ignition Delay
3. Flame Front Position

<u>Variables</u>

1. Engine Speed
2. Air-Fuel Ratio
3. Load
4. Valve Lift

Figure 4. Engine System and Output

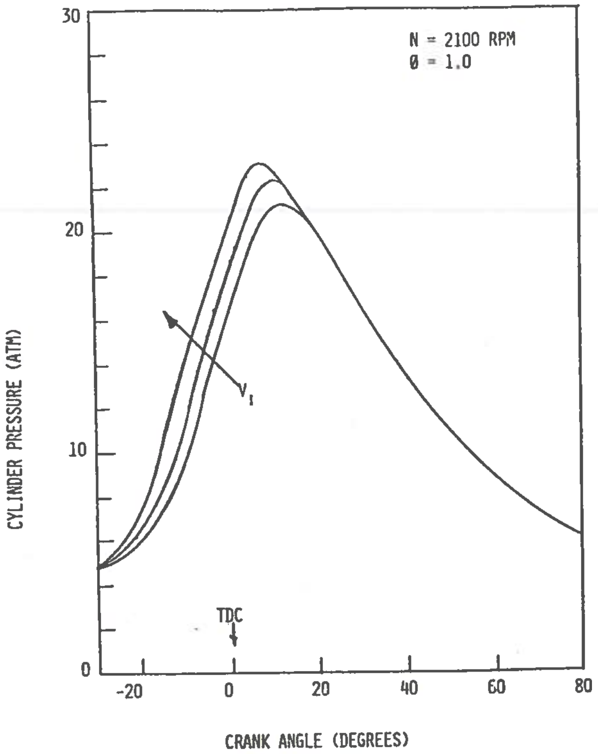


Figure 5. Cylinder Pressure Vs. Crank Angle

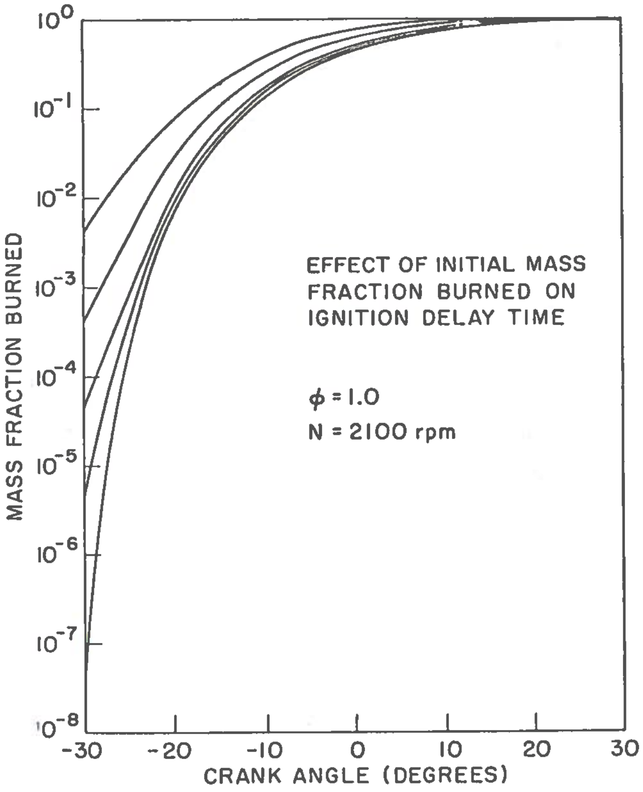


Figure 6. Mass Fraction Burned Vs. Crank Angle

of adding the flexibility for statistically varying eddy size, entrainment velocity, and air-fuel ratio. The experiments that compliment the combustion model are progressing satisfactorily and should begin to contribute to our knowledge by mid-year of this contract year.

Eventually the engine combustion model will be used as a framework for evaluating parameters such as turbulence levels, mixture non-homogeneities, and ignition system characteristics. For this task the combustion model will be merged with a cycle simulation model for performance evaluation.

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# EVALUATION OF ENGINE CONTROL PARAMETERS

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## ABSTRACT

The principal objectives of this contract include (1) a survey, evaluation and documentation of automobile engine control practices at the engine, engine control device and control systems levels, and (2) the performance of sensitivity analyses, supported by selected engine and chassis dynamometer tests, to determine the effects of various engine control parameters as well as improved control techniques and systems on important engine performance factors including fuel economy, emissions and driveability.

The scope of this work is limited to spark ignition engines of both conventional and lean burn designs. Alternative heat engines, including gas turbines, Rankine engines, diesels, stratified charge engines and Stirling engines have been evaluated or are being evaluated for potential use in automotive applications by a number of organizations.

The program has been divided into two distinct phases. Phase I is entirely analytic while Phase II involves both experiments and analyses. Currently, Phase I is the only funded portion of the program.

The objectives of Phase I will be met by three analytic tasks. Task A which has been completed, involved the organization of an Automobile Engine Control Workshop/Symposium, designed to provide a forum for technical interchange in the area of automobile engine control and to permit a basis of perspective with regard to potential benefits in fuel economy and emissions resulting from the use of improved control techniques. In Task B, the control systems and techniques of a number of selected automobile engines are reviewed with particular emphasis on the impact of changes in emission regulations on engine control system design and operation. Finally, Task C is concerned with the development of a methodology for identifying "best" engines and "best" control techniques in terms of fuel economy and emissions. In addition, this task involves the prediction of improvements in fuel economy that might be realized through the incorporation of more refined control approaches, and the selection of a number of "best" engines for potential testing in Phase II of the overall program.

Phase II of the program consists of five tasks which are designed to provide an initial set of reliable test data which are needed as the basis for a meaningful assessment of the impact of various control parameters on the performance and emission characteristics of the selected engines. First baseline fuel economy and emission maps will be obtained for the selected engines, either from the manufacturer or from dynamometer tests, and the data will then be analyzed to isolate the effects of specific engine and control system features on fuel economy and emissions. Then sensitivity tests and analyses will be conducted for the baseline engines considering a number of engine control parameters. These tests and analyses will be repeated for the selected engines after incorporation of improved control systems and techniques. The most improved engines will then be tested in vehicle installations on the dynamometer to determine their fuel economy and emissions characteristics over the Federal City and Highway driving cycles. Finally, the vehicle test data will be compared with the trends established from the engine dynamometer data and with the predictions made in Task C of Phase I.

The Automobile Engine Control Workshop/Symposium was conducted at DOT's Transportation Systems Center on 8, 9 July, 1975. The symposium was attended by approximately 80 individuals representing a number of domestic and foreign automobile manufacturers, universities, government agencies and engineering and consulting firms. A total of 19 papers were presented at the meeting and much of the material discussed is directly applicable to Task C of this particular study. A proceedings document is in preparation and will be available for distribution before the end of the year. A number of pertinent subject areas were addressed by the speakers, including:

1. Engine Modeling and Control Variables
2. Engine Technology
3. Optimization and Constraints
4. Impact of Emission Standards
5. Sensing and Control Techniques
6. Engine Mapping and Testing

In regard to engine control variables, a number of papers highlighted the interrelationships between various engine control parameters, such as spark advance, turbulence level, mixture homogeneity, air/fuel ratio and chamber shape, and important engine performance factors such as fuel consumption and emissions. Estimates were presented of potential improvements in fuel economy that might be achieved with improved engine design and control systems incorporating catalysts or thermal reactors.

In the engine technology area the emphasis was placed on lean engine concepts, and the required component modifications including high intensity ignition, increased intake air turbulence, improved fuel atomization and vaporization, and improved mixture distribution.

While some spark ignition engines have been operated successfully at air/fuel ratios beyond 25:1, it appears that the 18-20 air/fuel ratio range might be more desirable with regard to optimizing both fuel economy and emissions. Based on the available data it appears that lean engines would have the capability of meeting $NO_x$ standards as low as 1 gr/mile, but could not reach the 0.4 gr/mile level.

In the area of engine optimization and constraints, several papers stressed the impact of emission regulations on the optimization process of automobile engines. Because of the transient nature of automobile engine operation and the dependence of engine emissions on transient conditions, many individuals feel that dynamic engine optimization is urgently needed.

Several authors presented test data showing the impact of emission standards on the fuel consumption of current engines and discussed the engine technology required to meet these standards. Based on this information, it can be concluded that $NO_x$ levels below about 2 gr/mile require some spark retard in spark ignition engines resulting in a loss in fuel economy. Uncertainties regarding future $NO_x$ standards appear to inhibit the development of stratified charge engines by the automakers.

Several papers described various sensing and control techniques, including the measurement of exhaust gas species, air mass flow sensors, air flow modulation measurement of cylinder peak pressure and the application of microprocessors to automotive control systems. The non-availability of suitable sensors inhibits the development and application of advanced engine control systems.

With regard to engine mapping and testing, descriptions were presented of the Ford and General Motors mapping facilities. In the ensuing discussion a number of individuals stressed the importance and need of test facilities having transient capabilities, particularly with regard to emissions.

Task B efforts are devoted to the survey and documentation of the control approaches employed in a number of selected domestic and imported automobile engines/vehicles. As shown in Figure 1, four horsepower classes and five emission levels are being considered in the study, covering engine power outputs between 35 hp and 150 hp and emission levels between uncontrolled and 1975 California levels. Controllable parameters considered in this task are also listed in Table 1 and involve many engine components including the intake system, combustion chamber, carburetion and ignition systems, and the devices and techniques incorporated for emission control purposes. The principal output of this task is the documentation of the control practices employed by the auto manufacturers in meeting various levels of emission control. The basic engine and engine subsystem choices and settings, including engineering and other limitations associated with the control techniques utilized will also be documented.

Task C is concerned with the development of screening procedures and criteria for the identification of the "best" engines and "best" methods of control of currently available engines in terms of fuel economy, emissions and driveability, for the four engine categories selected for this study. This screening procedure will be applied to all engines considered in Task B, and two to four of these engines between 50 hp and 150 hp will be chosen for use in Phase II evaluation tests. In addition, efforts will be conducted to identify the reasons for the fuel consumption differences between average and "best" engines, and the differences in engine and control system design philosophies utilized by domestic and foreign automobile manufacturers will be highlighted. Finally, attempts will be made to project the ultimate fuel economy improvements of the "best" engines that might be achieved at various emission levels by means of engine modifications and incorporation of (1) simple control system technology and (2) sophisticated control system technology.

As shown in Table 2, a total of 28 engines - 12 domestic and 16 imported - were selected for further consideration in Task B of this study. Twenty-three engines are carbureted and five are equipped with fuel injection. Several factors were considered in the engine selection process, including sales volume over the past several years, number of years in production, use of fuel injection, incorporation of the engine in vehicles with or without catalysts, and the use of standard or automatic transmissions. At least one engine was chosen from each foreign country exporting to the United States to provide a means of identifying and assessing inherent design differences that might exist between domestic and imported engines.

Typical engine design and control system modifications incorporated by one automobile manufacturer for the purpose of meeting the emission regulations for the past 10 year period, are listed in Table 3. As indicated, positive crankcase ventilation (PVC) systems have been in use for many years; in fact PCV was employed in some engines as far back as 1961. While most manufacturers have expended considerable efforts in the past several years with regard to incorporating various engine modifications, including intake manifold and combustion chamber redesigns, further research and development in these areas would be needed combined with other techniques to achieve additional improvements in fuel economy and emissions. Distributor modifications date back to 1966 involving primarily the optimization of the centrifugal and vacuum advance schedules and the incorporation of improved timing accuracy and distributor manufacturing control.

In 1966, the first year of HC and CO regulation in California, initial modifications were made on the carburetor, including improved calibration and incorporation of an idle mixture limiter to prevent idle adjustment outside acceptable mixture ratio limits. To comply with more stringent 1970 emission standards, a number of additional carburetor modifications were implemented in 1970 including

## TABLE 1. TASK B — SURVEY OF ENGINE CONTROL PRACTICES

- SURVEY INCLUDES FOUR HORSEPOWER CLASSES AND FIVE EMISSION LEVELS
  - HORSEPOWER:
    - 35 - 50
    - 51 - 75
    - 76 - 100
    - 101 - 150
  - EMISSIONS:
    - UNCONTROLLED
    - 1974 FEDERAL STANDARDS
    - 1974 CALIFORNIA STANDARDS
    - 1975 FEDERAL STANDARDS
    - 1975 CALIFORNIA STANDARDS
- BASIC CONTROLLABLE PARAMETERS AND SENSING VARIABLES
  - ENGINE SPEED
  - MANIFOLD VACUUM
  - INTAKE AIR TEMPERATURE
  - INDUCTION SYSTEM DESIGN
  - COOLANT TEMPERATURE
  - VALVE TIMING
  - COMBUSTION CHAMBER DESIGN
  - SPARK ADVANCE
  - FUEL/AIR MIXTURE RATIO
  - FUEL METERING SYSTEM
  - EXHAUST GAS RECIRCULATION
  - SECONDARY AIR FLOW
  - COMPRESSION RATIO
  - SPARK INTENSITY AND DURATION
- TASK OUTPUT
  - CONTROL PRACTICES/SYSTEMS INCLUDING DISCUSSION OF ENGINEERING AND/OR OTHER LIMITATIONS

## TABLE 2. ENGINE SELECTION

| MANUFACTURER | CID | HP[1] | AUTOMOBILE MODELS | 1974 SALES percent | YEARS ON U. S. MARKET | DOT TEST | REASON FOR SELECTION |
|---|---|---|---|---|---|---|---|
| 35-50 HP | | | | | | | |
| VOLKSWAGEN | 96.7 | 48 | BEETLE | >70 | 10 | YES | ONLY ENGINE IN CLASS |
| 51-75 HP | | | | | | | |
| FIAT | 78.7 | 62 | 128 SERIES | >50 | >3 | NO | ITALIAN DESIGN |
| BRITISH LEYLAND | 91 | 54 | MG MIDGET | - | - | NO | ENGLISH DESIGN |
| NISSAN | 85.3 | 70 | B 210 | 30 | 1 | NO | MODERN JAPANESE DESIGN |
| TOYOTA | 96.9 | 75 | COROLLA, CARINA | 38 | 5 | NO | POPULAR JAPAN. DESIGN |
| VOLKSWAGEN | 89.7 | 70 | DASHER, RABBIT, SCIROCCO | 12 | 2 | YES | MODERN GERMAN ENGINE |
| 76-100 HP | | | | | | | |
| AMERICAN MOTORS | 232 | 90 | GREMLIN, HORNET, PACER | >35 | >10 | YES | LONG HISTORY |
| AMERICAN MOTORS | 258 | 95 | GREMLIN, PACER, HORNET | - | 5 | YES | POPULAR |
| CHRYSLER | 225 | 100 | DART, CORONET, VALIANT | 37 | >10 | YES | LONG HISTORY |
| FORD | 140 | 83 | PINTO, MUSTANG II, CAPRI | 21 | 2 | YES | POPULAR NEW ENGINE |
| FORD | 171 | 97 | PINTO, MUSTANG II, CAPRI | 8 | 2 | NO | MODERN ENGINE |
| FORD | 250 | 86 | MAVERICK, COMET, TORINO | 10 | 7 | YES | LONG HISTORY |
| GENERAL MOTORS | 140 | 78 | VEGA, MONZA | 11 | 5 | YES | POPULAR ENGINE |
| AUDI | 97 | 81 | FOX | 50 | 1 | NO | MODERN; FUEL INJECTION |
| AUDI | 114 | 95 | AUDI 100 | 50 | 4 | NO | FUEL INJECTION |
| BMW | 121 | 96 | 2002 | - | 8 | NO | HIGH PERFORMANCE |
| NISSAN | 119 | 97 | DATSUN 610; 620; 710 | 52 | 2 | YES | POPULAR ENGINE |
| PEUGEOT | 120 | 88 | PEUGEOT 504 | - | 5 | NO | FRENCH DESIGN |
| TOYOTA | 133.6 | 96 | CELICA, CORONA, | 53 | 1 | NO | POPULAR ENGINE |
| VOLVO | 121 | 98 | 242; 244; 245; 142 | 74 | >7 | YES | SWEDISH; LONG HISTORY |
| BRITISH LEYLAND | 110 | 78 | MGB; AUSTIN MARINA | 50 | >8 | NO | ENGLISH; LONG HISTORY |
| 101-150 HP | | | | | | | |
| AMERICAN MOTORS | 304 | 120 | GREMLIN, HORNET, | 25 | 6 | NO | POPULAR ENGINE |
| CHRYSLER | 318 | 150 | DART, VALIANT, DUSTER | 36 | >10 | YES | LONG HISTORY |
| FORD | 351 | 148 | GRANADA, TORINO, LTD | 21 | 7 | YES | LONG HISTORY |
| GENERAL MOTORS | 250 | 105 | CAMARO, NOVA, FIREBIRD | 7 | 9 | YES | LONG HISTORY |
| GENERAL MOTORS | 350 | 145 | IMPALA, DELTA, LE SABRE | 50 | 8 | YES | MOST POPULAR ENGINE |
| DAIMLER BENZ | 167.6 | 120 | 280 SERIES | - | 4 | NO | HIGH TECHNOLOGY COMP. |
| SAAB | 121 | 115 | 99 SERIES | >80 | 3 | YES | SWEDISH; FUEL INJECT. |

(1) 1975 HP, 49 STATES

## TABLE 3. TYPICAL CONTROL SYSTEMS AND TECHNIQUES

| | 1966 | 1970 | 1974 | 1975 |
|---|---|---|---|---|
| POSITIVE CRANKCASE VENTILATION SYSTEM | OPEN SYSTEM (F)<br>CLOSED SYSTEM (C | CLOSED SYSTEM | CLOSED SYSTEM | CLOSED SYSTEM |
| ENGINE MODIFICATIONS | NONE | CAMSHAFT<br>COMBUSTION CHAMBER<br>LOWER COMPRESSION RATIO<br>INTAKE MANIFOLD<br>INTAKE VALVE PORT<br>EXHAUST MANIFOLD HEAT CONTROL VALVE<br>THERMOSTAT TEMPERATURE CHANGE | CAMSHAFT<br>COMBUSTION CHAMBER<br>LOWER COMPRESSION RATIO<br>INTAKE MANIFOLD<br>INTAKE VALVE PORT<br>THERMOSTAT TEMPERATURE CHANGE | CAMSHAFT<br>COMBUSTION CHAMBER<br>LOWER COMPRESSION RATIO<br>EXHAUST MANIFOLD HEAT CONTROL VALVE |
| DISTRIBUTOR MODIFICATIONS | VACUUM CONTROL VALVE<br>MOD. SPARK ADVANCE<br>IMPROVED TIMING ACCURACY | SPARK ADVANCE MOD.<br>IMPROVED TIMING ACCURACY<br>IDLE SPARK RETARD<br>IMPROVED MANUFACTURING CONTROL | ADVANCE MODIFICATION<br>IMPROVED TIMING ACCURACY<br>IMPROVED MANUFACTURING CONTROL | ADVANCE MODIFICATION<br>IMPROVED TIMING ACCURACY |
| EVAPORATIVE EMISSION CONTROL SYSTEM | NONE | CARBON CANISTER (C) | CARBON CANISTER | CARBON CANISTER |
| CARBURETOR MODIFICATIONS | IDLE MIXTURE LIMITER<br>IMPROVED CALIBRATION | IDLE MIXTURE LIMITER<br>CALIBRATION REFINEMENTS<br>OFF IDLE MIXTURE ADJ<br>OFF IDLE AIR BLEED<br>CHOKE MODULATION<br>HOT IDLE COMPENSATOR<br>SOLENOID THROTTLE STOP | IDLE MIXTURE LIMITER<br>CHOKE REFINEMENTS<br>CARBORATION REFINEMENTS<br>BY-PASS IDLE AIR SYST.<br>CHOKE MODULATION IMPROVEMENTS<br>ELECTRIC ASSIST CHOKE<br>SMALLER PRIMARY VENTURI<br>LARGER SECOND VENTURI<br>TRIPLE VENTURI AIR SECTION<br>SOLENOID THROTTLE STOP<br>REVISED MAIN METERING | IDLE MIXTURE LIMITER<br>CHOKE REFINEMENTS<br>CARBURETOR REFINEMENTS<br>BY-PASS IDLE AIR SYSTEM<br>CHOKE MODULATION IMPROVEMENTS<br>ELECTRIC ASSIST CHOKE<br>SMALLER PRIMARY VENTURI<br>LARGER SECOND. VENTURI<br>TRIPLE VENTURI AIR SECTION<br>SOLENOID THROTTLE STOP<br>REVISED MAIN METERING<br>IDLE ENRICHMENT<br>ALTITUDE COMPENSATION<br>BY-PASS AIR SYSTEM |
| EXHAUST EMISSION CONTROL SYSTEMS | NONE | HEATED INLET AIR | HIGHER CAMSHAFT OVERLAP<br>EGR<br>SPARK ADVANCE CONTROL<br>AIR INJECTION (C)<br>HEATED INLET AIR | HIGHER CAMSHAFT OVERLAP<br>EGR<br>SPARK ADVANCE CONTROL<br>AIR INJECTION<br>HEATED INLET AIR CATALYST(S) |

further calibration and choke refinements and the use of a solenoid throttle stop which permits complete closing of the throttle to prevent "dieseling" of the engine after ignition has been turned off. Additional choke and carburetion refinements were incorporated in 1974. These include an electric choke assist unit which accelerates the warmup process of the thermostatic coil spring, resulting in lower HC and CO emissions during engine cold start. The primary venturi was reduced in size to increase the velocity of the air in the carburetor for better fuel atomization and mixture control in the low to medium load regime of the engine. Some carburetors were equipped with triple venturis for improved mixture control at low loads. Incorporation of a bypass air passage in the throttle flange transfers air from above the throttle blade to below the throttle blade. This results in better air/fuel mixture distribution and permits the use of leaner idle mixtures for added HC and CO control.

In 1975, additional carburetor improvements were incorporated including more accurate fuel metering, better mixture distribution and smaller manufacturing tolerances. In addition, a coolant controlled idle enrichment system was introduced which provides richer idle mixtures during the first 30 seconds of a cold start for improved vehicle driveability. Cars sold in California were equipped with an altitude compensation device which maintains a near constant air/fuel ratio at altitude by increasing the air supply to lean out the rich mixture that would otherwise be supplied by the carburetor. Some 1975 vehicles are equipped with a carburetor dashpot, which is designed to reduce the rate of throttle closure when the accelerator pedal is suddenly released. This unit provides additional control of the HC and CO emissions during vehicle deceleration.

Vehicle fuel economy trends are shown in Figure 1. covering the past 10 year period. The curves are based on EPA certification data and test data from EPA's surveillance test program. The curve at the bottom of the chart represents the 4500 lb. inertia weight class and includes vehicles from different manufacturers as well as different engine sizes. Also shown in the chart are curves representing the sales weighted average automobile fuel economy, as determined by Austin and Hellman of EPA, the fuel economy of two domestic 4500 lb. vehicle groups employing engines A and B, and the fuel economy of an imported vehicle equipped with engine C. All curves show deteriorating fuel economy between 1966 and 1974 which is attributed to increasingly stringent emission standards. Much of the sharp rise in fuel economy observed between 1974 and 1976 is directly related to the catalytic emission control systems utilized on these vehicles in 1975 and 1976 combined with improvements in engine design which permitted the use of more optimum spark timing and leaner mixture operation. Further improvements in carburetor and combustion chamber design and incorporation of dynamic EGR and air/fuel mixture control are projected to result in additional gains in fuel economy.

The centrifugal spark advance schedule of a typical domestic automobile engine is illustrated in Figure 2 as a function of model year and engine speed. As indicated some spark retard was introduced between 1968 and 1970 to provide additional HC and CO control. Between 1970 and 1974, the spark settings remained nearly constant on this engine while additional retard was utilized in 1975, particularly in the high speed regime. However, in 1975, the lower centrifugal advance was compensated for by an increase in vacuum advance, particularly in the medium to high load regime of the engine. This is illustrated in Figure 3 which shows the distributor vacuum advance of this engine versus model year and manifold vacuum. Except for the very high vacuum regime, the vacuum advance was reduced between 1968 and 1970 as a means of assisting in the control of HC and CO emissions. In 1971 and 1972, a number of design improvements were incorporated in the intake system, combustion chamber and camshaft which caused substantial reductions in HC and CO. As a result, it was possible to advance the spark for better fuel economy. Since

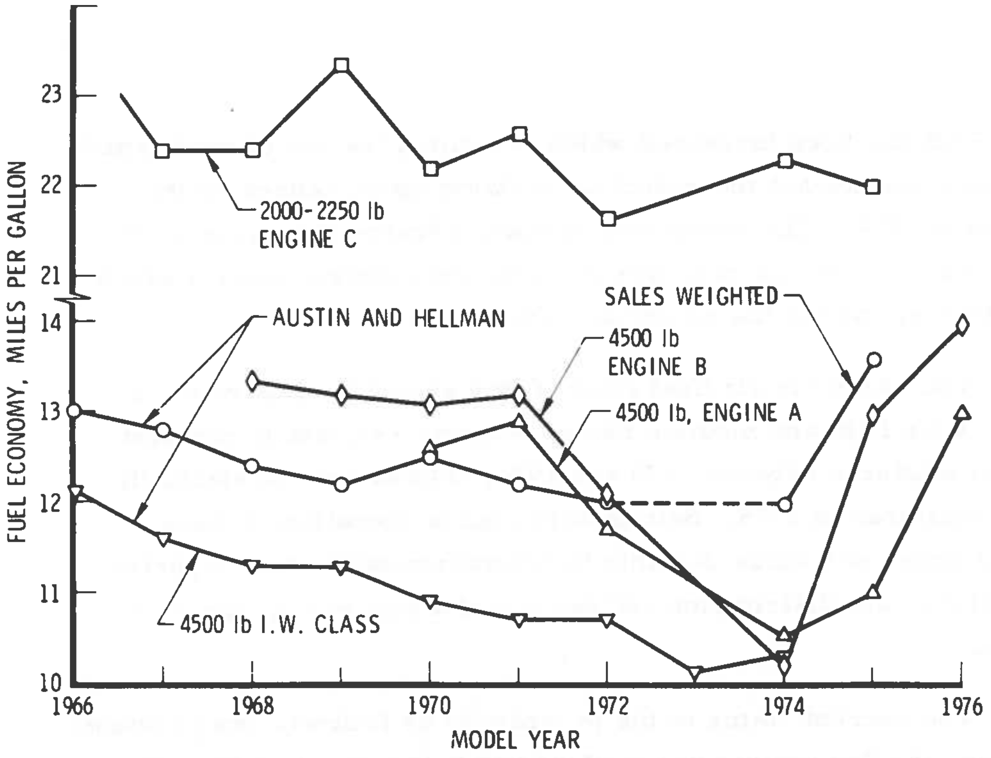

Figure 1. Vehicle Fuel Economy Trends — 1975 FTP

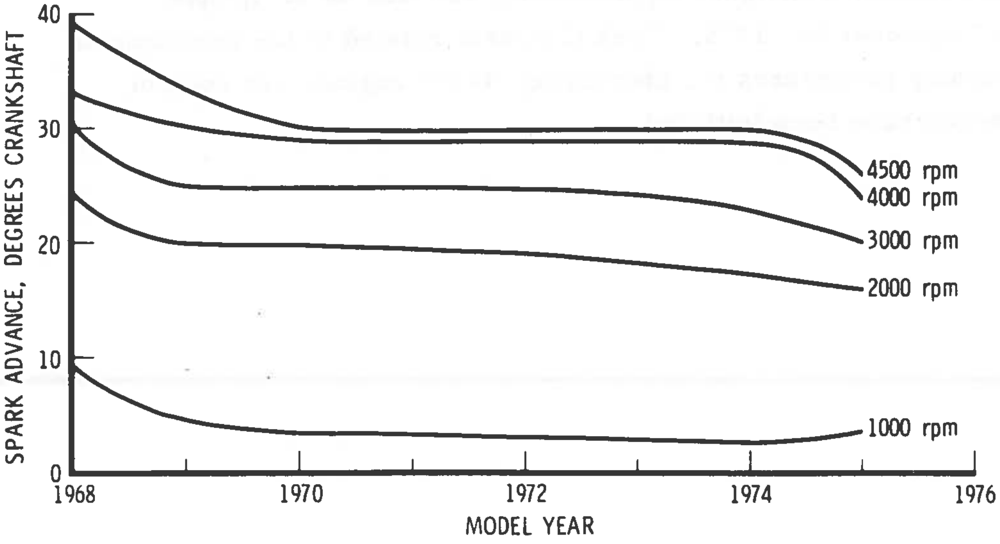

Figure 2. Typical Distributor Centrifugal Advance Schedule

1973, EGR has been increased which permitted the use of more spark advance to counteract the reduction in flame speed caused by the addition of EGR. The sharp rise in spark advance shown for 1975 is attributed to the use of a catalytic emission control system which permits operation of the engine at leaner air/fuel ratios.

The change in air/fuel ratio of this engine is illustrated in Figure 4 for light and medium loads, showing essentially constant air/fuel mixtures between 1970 and 1974, followed by substantially leaner mixtures in 1975. Satisfactory engine operation at these lean mixtures was made possible by improvements in fuel vaporization and mixture distribution and the use of a high energy ignition system.

The current status of the program is as follows. As previously stated, the Symposium proceedings are being prepared and are scheduled for distribution on or before December 31, 1975. Work on Task B which involves the documentation and evaluation of current and past control techniques is proceeding and will be completed before December 15, 1975. Task C efforts related to the development of screening procedures for identifying "best" engines and control approaches have been initiated.

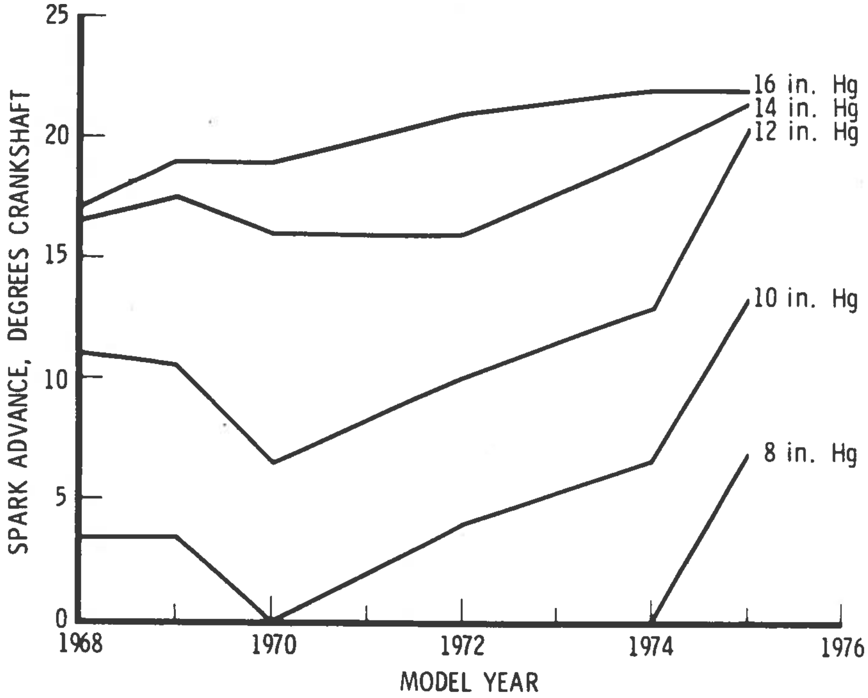

Figure 3. Typical Distributor Vacuum Advance Schedule

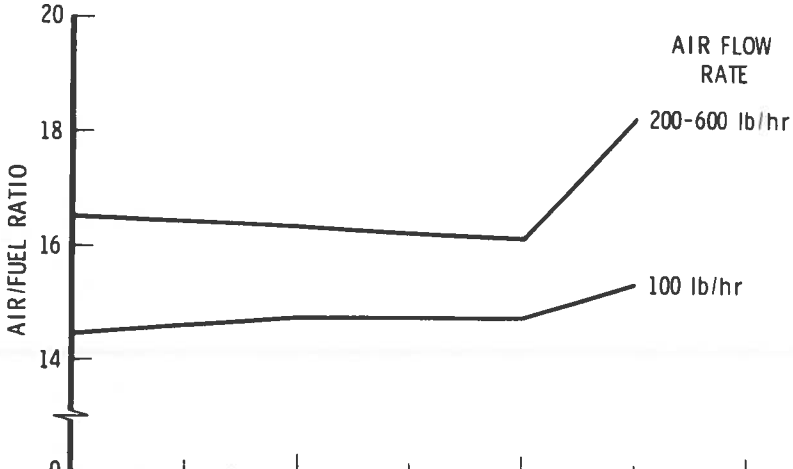

Figure 4. Typical Air/Fuel Ratio Schedule — Light Load

# HYBRID VEHICLE TECHNOLOGY CONSTRAINTS AND APPLICATION ASSESSMENT

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## ABSTRACT

A study of hybrid automotive vehicles is being conducted to ascertain their potential for reducing public transportation energy consumption. The objectives of the study are (1) to identify and characterize meaningful hybrid vehicle configurations having potential applicability to passenger car, van, and bus use modes; (2) to determine the feasibility of implementation of selected hybrid vehicle configurations, (3) to determine the impact of such hybrid vehicle usage on vehicle-related petroleum-based fuel consumption and exhaust emissions, and (4) to determine the impact of hybrid vehicle use on the ability to accommodate a different energy resource base (using energy supplied by electric generating stations) in the longer term.

The basic approach in this study is the use of empirical component performance data in a versatile vehicle simulation computer program. Principal emphasis is on heat engine/battery and heat engine/flywheel configurations.

A major portion of the analytical effort is devoted to a sensitivity analysis that will reveal the effect of changes in powertrain and vehicle characteristics on energy consumption and exhaust emissions. This paper presents an overview of results to date, including selected examples of output from the computer based analysis.

## INTRODUCTION

The study effort under discussion in this paper is structured to ascertain the potential of hybrid systems for reducing public transportation energy consumption associated with highway vehicles. The term "hybrid system" refers to the combined use of a heat engine and an energy storage device for providing propulsive power in an automotive powertrain. The concept relies on the energy storage device (such as a battery) supplying rapidly fluctuating power requirements so that the heat engine can deliver power in a slower and more efficient manner than found in the conventional automotive powertrain.

Fundamental to the basic approach in this study is the use of empirical data for analytically predicting the operating performance of each major element in the vehicle powertrain. This required the acquisition, review, updating, and summarization of data from previous hybrid vehicle studies and test programs as well as from individual manufacturer's component data sheets.

A versatile computer program is being developed to use these data in a simulation model of powertrain operation during vehicle motion over specific driving cycles. It is capable of sizing components and of altering component performance characteristics and specified vehicle performance requirements in sequential steps from baseline values so that parametric studies can be performed. The intent of such studies is to show how changes in performance affect vehicle-related energy consumption and exhaust emissions. Subsequent analysis will then indicate what technological constraints could inhibit vehicle implementation and under what types of applications hybrid vehicles would have a meaningful advantage over other types of vehicles.

The results of the computer-based analysis are incomplete at this time. Therefore, this paper presents some selected examples of progress to date in evaluating operation of the hybrid automobile powertrain and in determining the energy consumption and exhaust emissions of the hybrid automobile relative to conventional cars.

## DISCUSSION

### 1. Types of Vehicles and Powertrains Under Consideration

The various classes of highway vehicles to be evaluated in this study are:

a) full-size (six-passenger) car
b) sub-compact car
c) delivery van
d) metropolitan transit bus

and, for the hybrid powertrain in each vehicle, the components to be characterized by performance maps include heat engines, electric motors, electric generators, transmissions, and energy storage systems. Of the numerous energy storage techniques suitable for highway vehicles, only rechargeable batteries and flywheels have performance characteristics that are sufficiently defined for use in the vehicle simulation computer program.

The methods proposed for delivering power to the vehicle drivewheels are as numerous as the powertrain components. A consolidation of these methods into two configurations, series and parallel, is deemed sufficient to define the relative energy consumption and exhaust emissions of hybrid vehicles. A schematic of these two forms of power flow is presented in Figure 1.

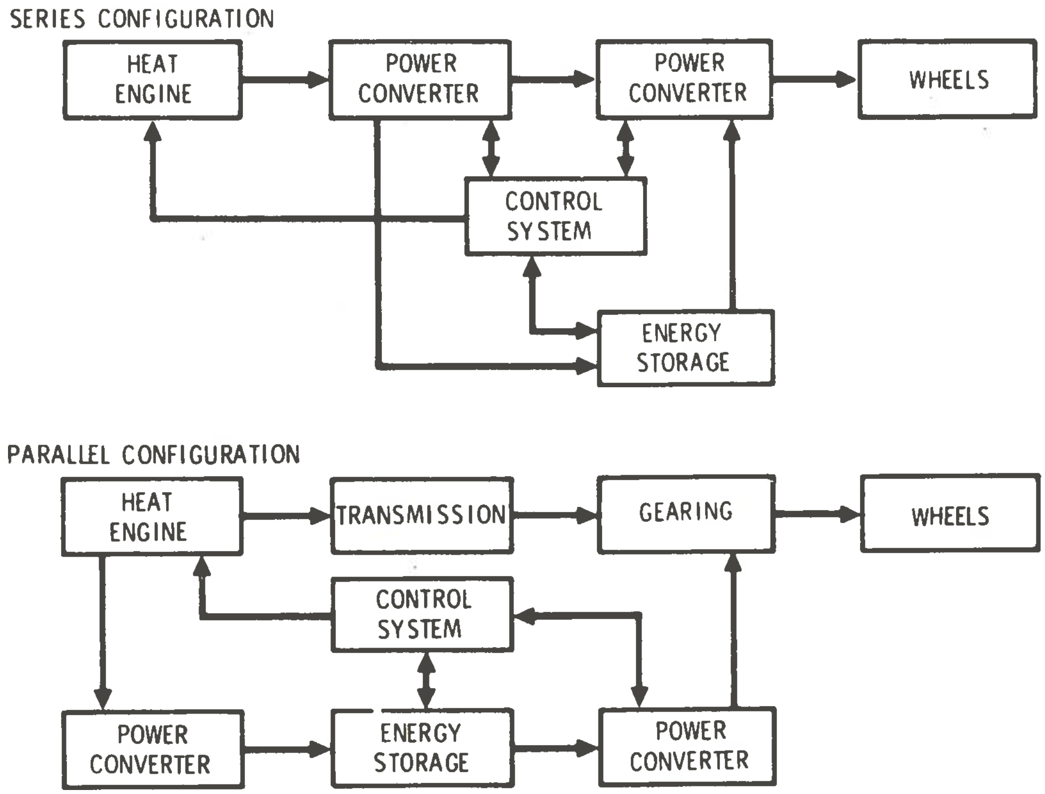

Figure 1. Hybrid Vehicle Powertrain Schematic

The parallel configuration, in contrast to the series configuration, allows a portion of the engine power to bypass the energy storage device and be delivered directly to the drive wheels. The box labeled "heat engine" will be represented for the most part by a spark ignition, gasoline-fueled, reciprocating piston engine delivering energy for vehicle cruise power, accessory loads, and recharge of the energy storage system (which provides power for vehicle acceleration). In the case of battery energy storage, the boxes labelled "power converter" refer to a generator (adjacent to the heat engine) and a motor (adjacent to the drive wheels). For flywheel energy storage, these components are replaced by continuously variable transmissions, and in the series configuration, the power flow path between the two "power converter" boxes is disconnected.

Additional flexibility in operation of the hybrid powertrain is considered in this study by including recharging of the energy storage device from stationary power sources (e.g., wall power outlet fed by electric generating station) as well as from the on-board heat engine. This concept embodies the potential for use of nonpetroleum-based energy sources (viz. coal, nuclear, hydro-electric) for a portion of vehicle propulsion needs, and the partial relocation of emissions to remote stationary sources.

## 2. Computational Variables for Parametric Analysis

A large number of factors can influence the performance of the hybrid vehicle. A summary of the major independent variables can be divided as follows:

Vehicle related
- design cruise speed
- design peak acceleration
- accessory load
- curb weight
- driving cycle characteristics

Powertrain related
- component efficiency
- heat engine specific fuel consumption and emissions
- heat engine contribution to recharge of energy storage system

The prime dependent variables of interest are vehicle energy consumption (both petroleum-based and nonpetroleum-based), exhaust emissions (from both mobile and stationary sources), and operating range. The operating range will be a function of two factors: the amount of fuel stored in the vehicle tank and the capacity of the energy storage system.

### 3. Selected Examples from Computer-Based Analysis

To illustrate the type of information being generated in this study, a limited number of results obtained by use of the Vehicle Simulation Computer Program are presented in Figures 2 - 9. A 4000 pound car powered by a hybrid heat engine/battery system in a series configuration was selected for this example.

Typical results for component sizing are the curves shown in Figures 2 and 3. Figure 2 illustrates the variation of electric motor weight with vehicle design peak acceleration time and with vehicle design cruise speed. For cruise speeds of 45, 55, and 65 mph, motor weight is influenced by both acceleration time and cruise speed with the lowest weight found at the lowest speed and longest acceleration time. At 80 mph, the cruise speed dominates over acceleration in sizing the motor.

A somewhat opposite set of characteristics is shown for battery weight in Figure 3. This is because a fixed powertrain weight of 1500 pounds was selected for the 4000 pound car, and allowable battery weight is determined by subtracting all other component weights from the allowable 1500 pounds.

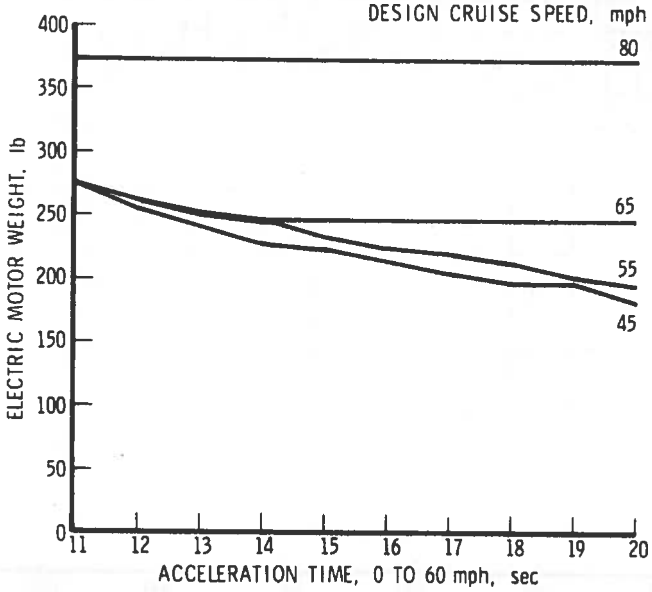

Figure 2. Powertrain Component Sizing — Hybrid Heat Engine/Battery System, 4000 Lb Car — Electric Motor Weight Vs. Acceleration Time

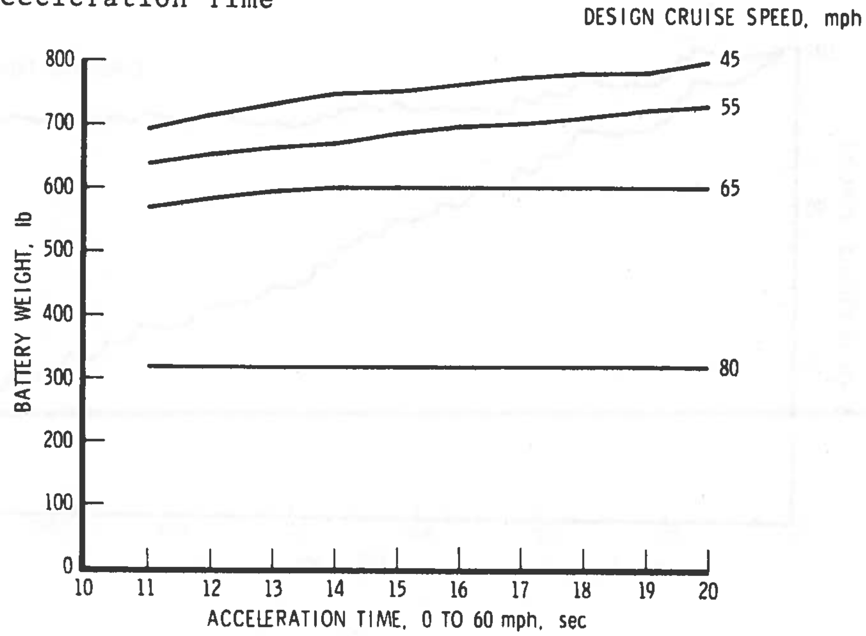

Figure 3. Powertrain Component Sizing – Hybrid Heat Engine/Battery System, 4000 Lb Car — Battery Weight Vs. Accleration Time

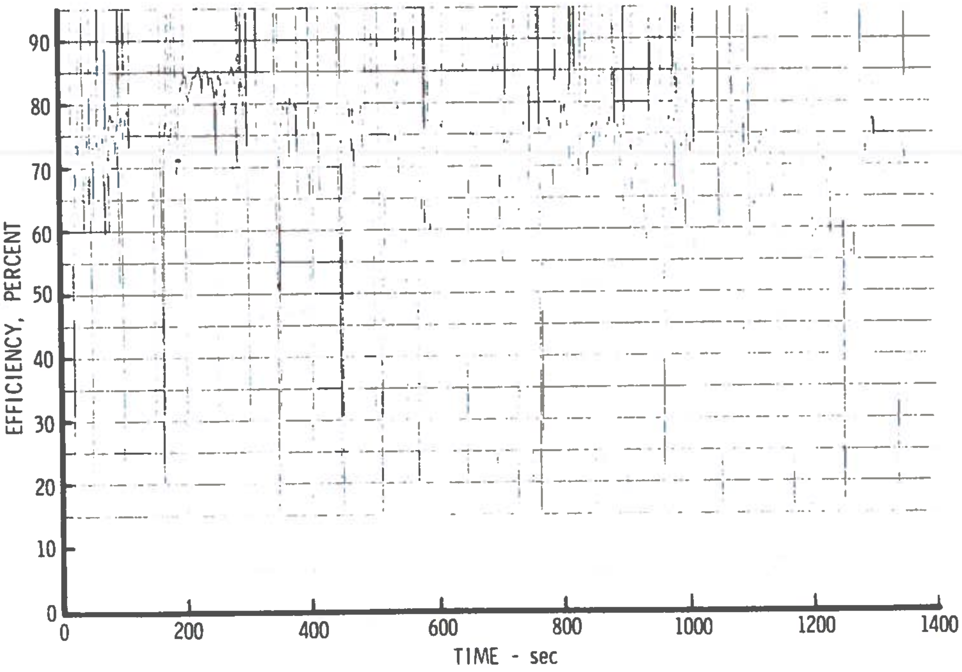

Figure 4. Motor Efficiency Over Federal Emissions Test Driving Cycle — 4000 Lb Car

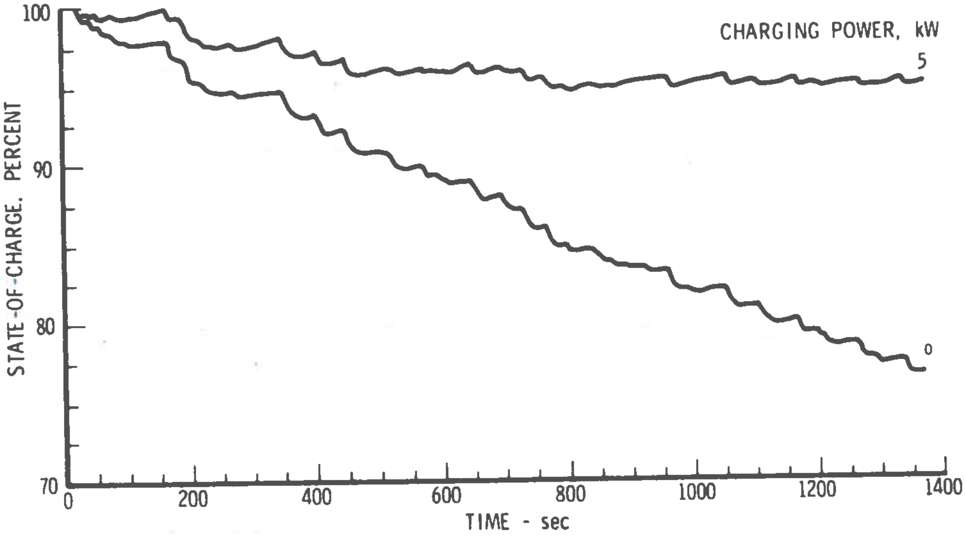

Figure 5. Battery State of Charge Over Federal Emissions Test Driving Cycle — 4000 Lb Car

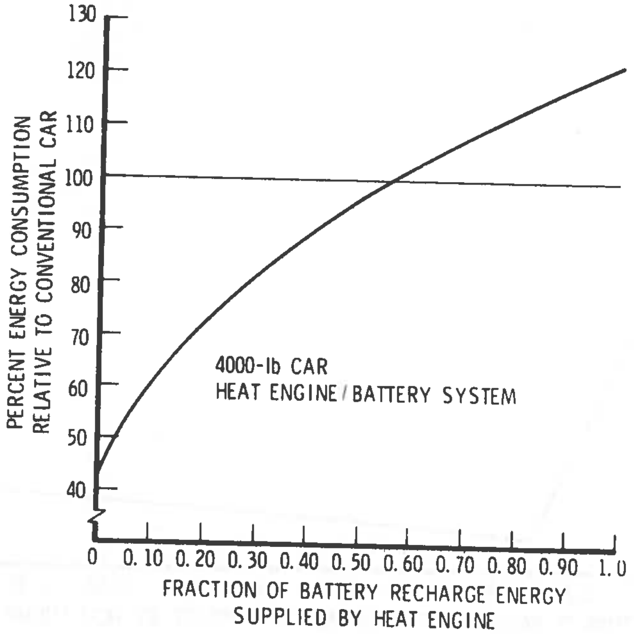

Figure 6. Hybrid Vehicle Relative Energy Consumption – Vehicle Fuel Consumption Only

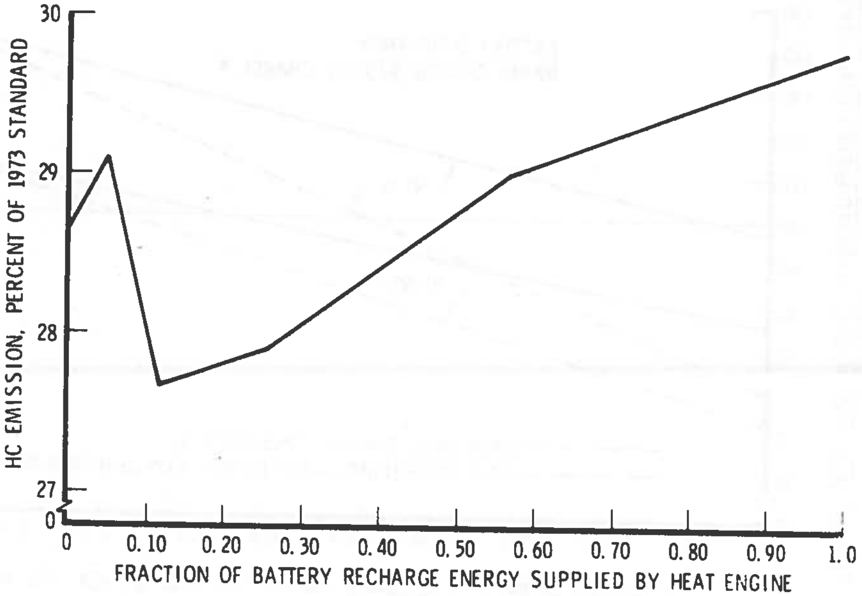

Figure 7. Hydrocarbon Emissions – Federal Emissions Test Driving Cycle, 4000 Lb Car – Vehicle Emissions Only

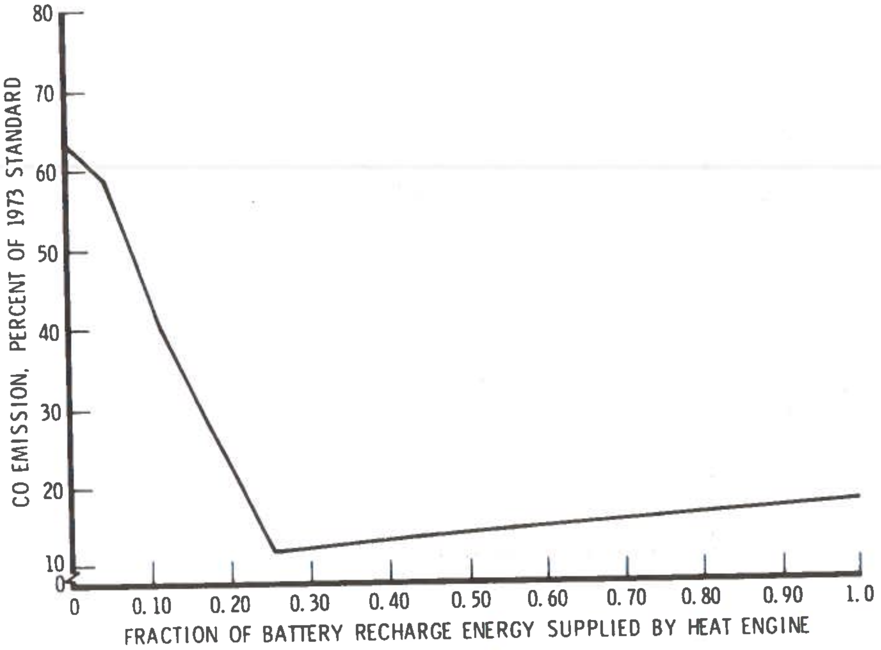

Figure 8. Carbon Monoxide Emissions — Federal Emissions Test Driving Cycle 4000 Lb Car — Vehicle Emissions Only

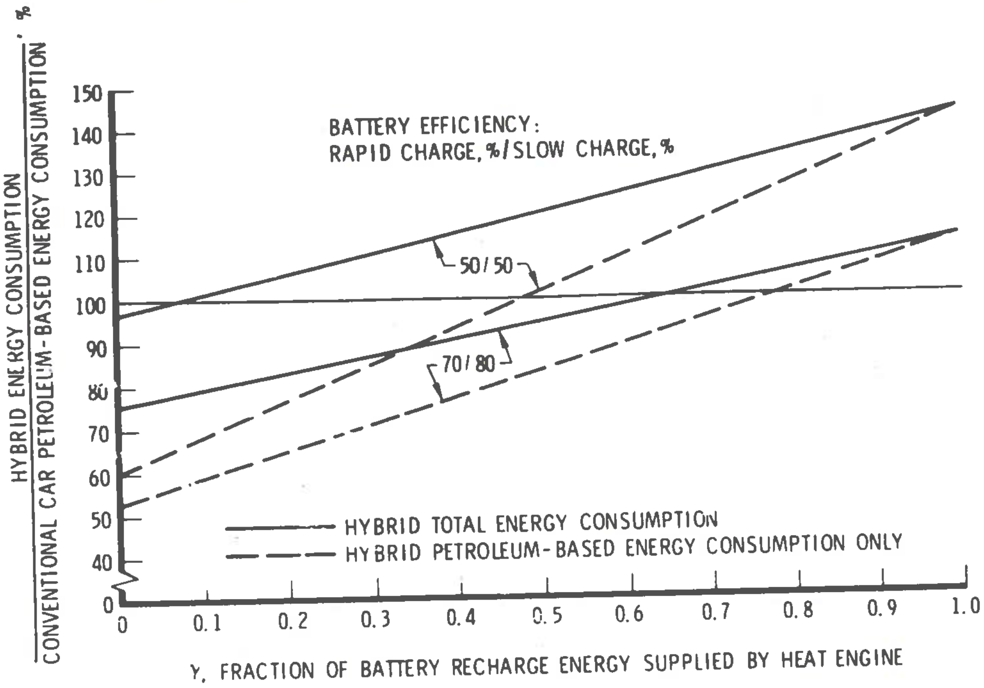

Figure 9. Effect of Battery Charge Efficiency on Hybrid Vehicle Energy Consumption

The efficiency of the electric drive motor during simulated vehicle motion over the 1371-second Federal Emissions Test Driving Cycle (FETDC) is shown in Figure 4. Generally, the efficiency lies between 70% and 80%; occasional reductions to levels as low as 10% occur during the initial period of acceleration following a vehicle stop. Values above 90% are a computational simplification introduced during vehicle deceleration or when the vehicle has stopped and are not used in the analysis that accounts for powertrain energy losses.

During the FETDC, the battery state-of-charge will continue to decrease at a rate depending on battery energy capacity, battery recharge rate from the engine-driven electric generator, and vehicle power requirements for acceleration. Figure 5 shows the characteristics of a nickel-zinc battery when recharge power is changed from zero to 5 kilowatts.

An example of the vehicle performance summary information being generated by the computer program is presented in Figures 6 - 8 for a vehicle with an 80 mph design cruise speed operating over the FETDC. In Figure 6, the hybrid vehicle energy consumption relative to a 1973 model year conventional car of the same weight is shown as a function of the fraction of battery recharge energy supplied by the on-board heat engine. (At a value of zero on the abscissa the engine supplies only vehicle cruise power and accessory power needs while, at a value of 1.0, it supplies, in addition, all battery recharge needs.) Figures 7 and 8 show hydrocarbon and carbon monoxide exhaust emissions relative to the 1973 Federal Standards for light duty vehicles.

The aforementioned energy consumption and emissions curves were given for the vehicle only. To the levels shown must be added the contribution of the stationary electric generating plant whenever the on-board heat engine does not supply all recharge energy for the battery. These results were not available from the computer program at this time, but an indication of the results to be expected are shown in Figure 9 for generating station characteristics representative of the nationwide average. (These curves are from an earlier analysis conducted without the benefit of the Vehicle Simulation Computer Program.)

In addition to showing the relative energy consumption of the hybrid car for both petroleum-based and nonpetroleum-based fuel, the curves also illustrate the marked impact component performance (in this case, battery efficiency) can have on vehicle energy consumption. Because each component in turn may have a similar impact, the matching of components to achieve a satisfactory overall powertrain efficiency is a difficult task and is almost akin to performing a system design for each and every vehicle application.

## FUTURE ACTIVITIES

The remainder of the study will be devoted primarily to completion of the parametric analysis and comparing hybrid vehicles to both conventional and non-conventional vehicles (such as battery-powered all-electric cars). This will be followed by a determination of powertrain configurations and vehicle performance requirements for selected applications of the hybrid vehicle so that the potential for transportation energy savings can be ascertained.

# SATISFYING AUTOMOTIVE FLEET FUEL DEMAND AND ITS IMPACT ON THE OIL REFINING INDUSTRY

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## ABSTRACT

Since virtually all transportation fuels are based on petroleum, it is essential to include petroleum refining in any assessment of potential changes in the transportation system. The automotive fleet, in particular, consumes about half of the total petroleum consumed in the United States. To provide a technologically sound basis for the assessment of potential changes in the automotive fleet, this project calls for the development of a computer-based mathematical model of the U.S. petroleum refining industry. This industry model is to include refinery aggregations by Petroleum Administration for Defense (PAD) districts. Within each district, refining modes will be included to represent variations in refinery size, feedstock quality, and operating severity. To assure technological consistency, these refining modes in the industry model are being developed with a detailed refinery linear programming model. The various PAD districts will be linked by the existing pipeline and water transportation network. Typical problems to be assessed with the use of the industry model include:

- A potential shift from gasoline to diesel engines.
- Determination of the optimum octane level for gasoline considering improved engine efficiency versus decreased refining efficiency.
- The potential requirement of sulfur removal from gasoline.

## Introduction

The interactions of the U.S. transportation system and the oil refining industry are extensive. Nearly half of the U.S. refinery output volume is motor gasoline, in addition to substantial quantities of automotive diesel fuel, jet fuel, and bunker fuel. Virtually all of the energy consumed in U.S. transportation is currently in the form of a petroleum product. A few exceptions exist such as electric transit systems, and there is some potential for replacement of petroleum-based fuels with alcohols or other substances which may be derived from non-petroleum sources. However, for the next 10 to 20 year period it does not appear likely that petroleum fuels for transportation will be substantially displaced by non-petroleum alternatives. Thus, the petroleum refining industry is expected to continue to play a critical role in supplying the basic energy requirements of the U.S. transportation system.

Concern for environmental quality and energy conservation in recent years has resulted in the automobile being identified as a major offender in both the emission of air pollutants and the inefficient use of fuel. A number of changes to the automobile have been proposed (and implemented) to lessen the detrimental effects of the automobile in both the environmental and energy use areas. A prime example of such a change is the requirement for making unleaded gasoline to accommodate the catalytic converter. Other potential changes to the automobile could have equally profound impacts on the oil refining industry.

To provide a technologically sound basis for assessing the impacts on the oil refining industry of such changes the objectives of this project are two-fold.

(1) Develop a mathematical modeling system of the U.S. petroleum refining industry, consisting of:

(a) A detailed refinery model

(b) A refining industry model.

(2) Implement the models in the analysis of the impact on the refining industry of specific potential changes in the fuel requirements of the automotive fleet.

To address these objectives in greater detail, it is useful to examine first the characteristics of a typical refinery before attempting to look at the industry as a whole. A logical first step in this effort is to define the basic problem of petroleum refining. Simply stated, the distilled volume fractions of crude oil do not, in general, match the relative market demand volumes for the corresponding products. Similarly the qualities of the crude oil fractions do not generally meet the required qualities of the corresponding products. As shown graphically in Figure 1, the major imbalance in both volume and quality occurs in the gasoline distillation range. Even from the relatively light crude oil depicted in Figure 1, the yield of indigenous (so-called straight-run) naphtha is about 33 volume percent of the crude oil, as compared with the U.S. gasoline production of about 50 percent of the barrel of products. The major quality deficiency of straight-run naphtha is its engine knock characteristic as measured by the empirical octane rating. The Research Octane Number (RON) of straight-run naphtha is typically in the range of 60 to 70, as compared to gasoline product requirements of 91 to 100.

The volume and quality discrepancies between the straight-run fractions and fuel products are generally less for the middle-distillates--jet fuel, diesel, and home-heating oil--than for gasoline. Smoke point is generally the critical specification for kerosene type jet fuel, cetane number for diesel fuel, and sulfur and pour point for fuel oils No. 2 through No. 6.

Over the years the petroleum refining industry has evolved the process technology to produce marketable volumes of specification products from various qualities of crude oils. Although no two refineries in the United States are identical in the application of the various refining processes, there is considerable uniformity in the types of processes used.

As shown in the typical refinery, depicted in Figure 2, catalytic reforming is the major process used to increase the octane number of straight-run naphtha. Catalytic cracking is the major process used to convert heavy distillate oils to gasoline. The light olefins--propylene and butylene--by-products of catalytic cracking are generally reacted with isobutane in a process called alkylation to produce a high-quality gasoline blend stock. Hydrocracking, a development of the 1960s, is used in many refineries to supplement the catalytic crackers in the production of additional gasoline and jet fuel.

Residual oil processing in U.S. refineries has primarily been directed to converting much of this fraction to lighter, more valuable products. Thermal cracking processes ranging in severity from visbreaking to coking are the major processes in general refinery use for resid reduction, along with a few applications of solvent deasphalting. As the prices of low-sulfur residual fuel oil have moved closer to

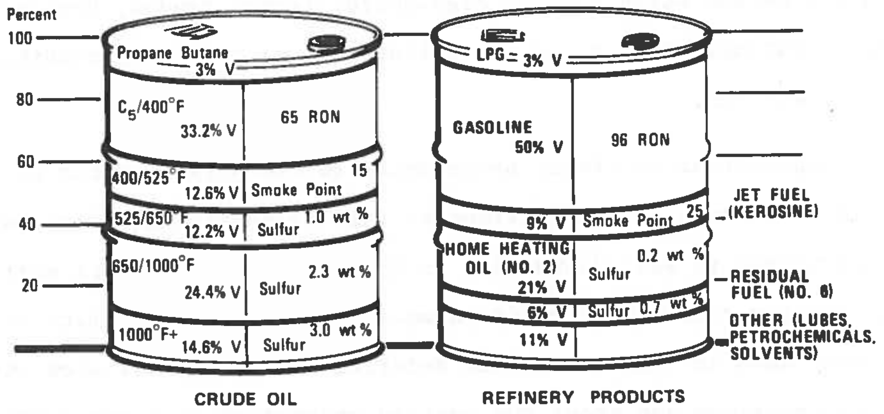

Figure 1. Basic Refinery Functions

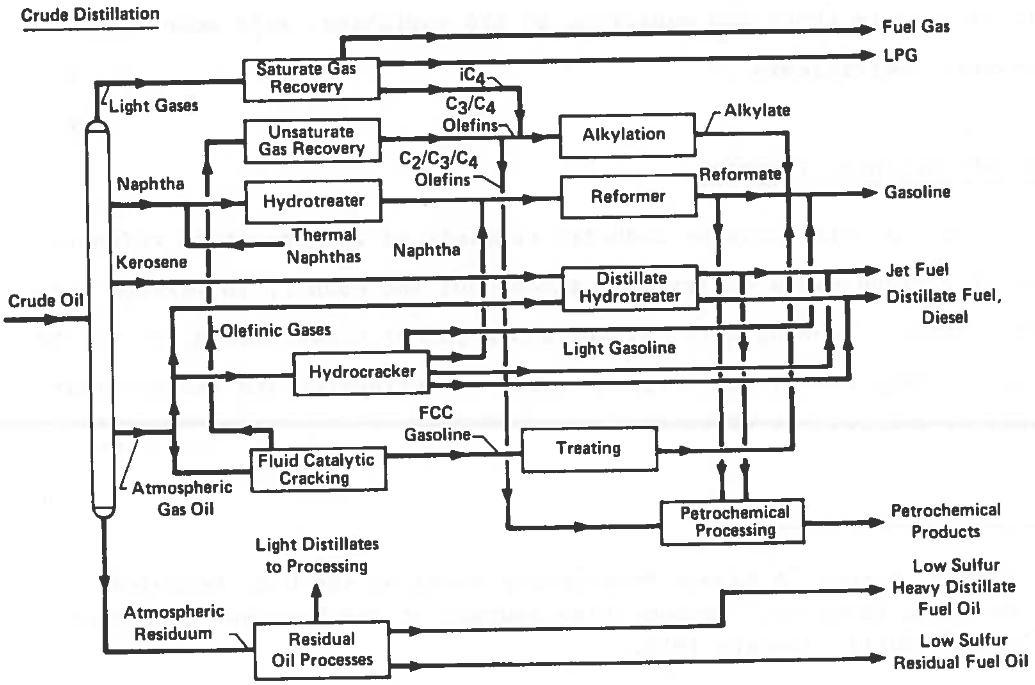

Figure 2. Typical Refinery Process Flow

distillate and gasoline prices, there has developed considerable interest in resid hydrodesulfurization technology, and the first installations of this type of process are currently under construction.

In refineries which process high-sulfur (sour) crudes, hydroprocessing is extensively applied for sulfur removal from both naphtha and distillate streams.

The application of linear programming to refinery modeling was one of the early successful applications of this mathematical technique. Since the method is well documented in the literature,* let it suffice here to briefly present the major parameters and characteristics of the model being used in this work. The detailed refinery model uses ten crude oil fractions and about 200 quality characteristics per crude. Over 30 process options are included with the appropriate yield streams, blending values, investment, and operating cost factors. The refinery model has about 25 fuel and petrochemical product options and includes 35 blend specifications for the six major fuel products. The resulting matrix size is about 330 equations by 570 variables, with some 4,800 non-zero coefficients.

## The Oil Refining Industry

The U.S. oil refining industry consists of 259 operating refineries of various sizes distributed throughout the country in various concentrations. Looking first at the geographical distribution, it may be seen in Table 1 that the largest number of refineries and the greatest share of capacity is located in Petroleum Administration for Defense

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* Alan S. Manne, "A Linear Programming Model of the U.S. Petroleum Refining Industry," Econometrica Journal of the Econometric Society, Volume 26(1), January 1958.

(PAD) District III, which includes the Gulf Coast states. A significant portion of the PAD III refinery output is transported to the East Coast markets by coastal tankers and products pipelines.

The distribution of refineries by size is also a significant parameter in a study of the industry. There are significant economies of scale in petroleum refining, and the larger plants are generally more flexible in adjusting to shifts in the feedstock qualities and product demand. On the other hand, some of the small refiners efficiently serve market areas outside of the transportation cost equalized tributary areas of the large refiners. As shown in Table 2, 5 percent of the U.S. capacity rests in refineries of less than 20,000 barrels per day, which account for 42 percent of the number of U.S. refineries. At the other end of the scale, nearly 60 percent of the U.S. refining capacity exists in plants greater than 100,000 barrel-per-day size, which account for only 18 percent of the number of refineries.

A third characteristic which has a significant impact on the flexibility of the industry to adjust to changes in product mix or product quality is the application of "downstream" processes. As shown in Table 3, the major processes downstream of the primary crude distillation are the vacuum distillation of the residual stream from the primary crude unit, the catalytic cracking unit, catalytic reforming, and the various applications of hydro-processing. Since several of these processes are used in sequence, the percentages do not add to 100 percent.

## Refining Industry Model

With the preceding description of the refining industry as background, it is appropriate at this point to address the issue of modeling the refining industry. A logical first step in this effort is to spell out the modeling objectives in greater detail, followed by discussion of the scope, modeling philosophy, and validation approach.

TABLE 1. REFINING INDUSTRY – GEOGRAPHICAL DISTRIBUTION

| REGION | PAD DISTRICT | NUMBER OF REFINERIES | CAPACITY MBPD | % OF CAPACITY |
|---|---|---|---|---|
| East Coast | I | 28 | 1678 | 11 |
| Midwest | II | 68 | 4030 | 28 |
| Gulf Coast | III | 83 | 6132 | 41 |
| Rocky Mountain | IV | 29 | 547 | 4 |
| West Coast | V | 51 | 2432 | 16 |
|  | TOTAL | 259 | 14,819 | 100 |

TABLE 2. REFINING INDUSTRY – PLANT SIZE DISTRIBUTION

| CLASS, MBPD | NUMBER | % OF NO. | CAPACITY MBPD | % OF CAPACITY |
|---|---|---|---|---|
| 0-20 | 109 | 42 | 805 | 5 |
| 20-50 | 65 | 25 | 2249 | 15 |
| 50-100 | 40 | 15 | 3002 | 21 |
| 100-200 | 30 | 12 | 4149 | 28 |
| 200+ | 15 | 6 | 4614 | 31 |
|  | 259 | 100 | 14,819 | 100 |

TABLE 3. REFINING INDUSTRY – PROCESS APPLICATION

| PROCESS | % OF CRUDE |
|---|---|
| Vacuum Distillation | 35.6 |
| Catalytic Cracking | 30.2 |
| Catalytic Reforming | 22.4 |
| Alkylation | 5.6 |
| Hydrocracking | 5.7 |
| Hydro-processing | 38.5 |
| Coking | 6.7 |
| Lube Production | 1.4 |
| Asphalt Production | 4.4 |
| BTX Production | 1.1 |

The basic objective of the industry model is to assess the impact on the oil refining industry of potential changes in the automotive fleet. The model is to permit assessment of:

- The industry availability of fuel product slates different from those currently produced
- Capital and energy requirements to effect such changes
- Impacts on various sectors of the industry by geographic and refinery size classification
- The impacts on supplies of supplemental feedstocks such as natural gas liquids
- The impacts on industries related to petroleum refining such as petrochemicals.

The scope of the model will include the U.S. refining industry, aggregated by PAD districts. The product and crude oil logistics will include major crude oil and product pipelines and marine transportation.

As a modeling philosophy, the general linearity of the industry suggests the applicability of linear programming (LP) as the basic framework. With well developed LP mathematical software systems readily available, the project efforts can be concentrated on the technical and economic issues involved rather than on programming of mathematical algorithms. In addition, the LP procedure inherently provides the marginal cost impact of variables operating against input limits. The aggregation by PAD districts is selected for consistency with the Bureau of Mines data base on refinery yields and crude oil and product movements. The optimization objective of such a model is typically that of minimizing cost. However, in the current situation of controlled prices, it appears prudent to include provisions for other objectives such as energy or capital minimization.

The final stage of model building is the validation phase. In this effort the model will be called upon to match the statistical data of the 1972-74 period.

The conceptual structure of the industry model is presented in Figures 3 and 4. Figure 3 shows a simplified submatrix of the refining industry in one PAD district. In the actual model it is anticipated that the refining industry matrix will be considerably larger than that depicted in Figure 3, to encompass additional types of refineries and additional operating modes for each type. As shown, the single district refining industry matrix includes a large and small refinery, each with a sweet and sour crude operation, and each of these with a typical conversion, low conversion, and high conversion operating modes. The rows of the matrix correspond to the input feedstocks, the products output, and the resources used, including purchased utilities, fuels, additives, labor, and capital for new facilities. The rows (equations) serve to add the production and requirements of each district's refining industry.

The refinery output totals are transferred to a second set of equations (rows) which define the transportation module as shown in Figure 4. The transportation module serves to link the given district with product transfers to and from other districts to meet the given district's demand. Product demands are generated externally and supplied as input to the model.

## Potential Uses of the Refining Industry Model

In the search for a more efficient and less polluting automobile, a number of changes have been proposed which would affect the refining industry. One such change is a potential shift to increase use of automotive diesel engines to benefit from the higher efficiency of the

|  | LARGE REFINERY |  |  |  |  |  | SMALL REFINERY |  |  |  |  |  | INCRE. HYDRO-TREAT | Σ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | SOUR CRUDE |  |  | SWEET |  |  | SOUR |  |  | SWEET |  |  |  |  |
|  | BASE OPERATION | HIGH CONV. | LOW CONV. | BASE | HC | LC | BASE | HC | LC | BASE | HC | LC |  |  |
| Crude | – |  |  |  |  |  |  |  |  |  |  |  |  | – |
| Butanes | – |  |  |  |  |  |  |  |  |  |  |  |  | – |
| LPG | + |  |  |  |  |  |  |  |  |  |  |  |  | + |
| Prem. Gasoline | + |  |  |  |  |  |  |  |  |  |  |  |  | + |
| Reg. Gasoline | + |  |  |  |  |  |  |  |  |  |  |  |  | + |
| Lead-free Gasoline | + |  |  |  |  |  |  |  |  |  |  |  |  | + |
| Sulfur-free Gasoline | + |  |  |  |  |  |  |  |  |  |  |  |  | + |
| Jet Fuel | + |  |  |  |  |  |  |  |  |  |  |  |  | + |
| Diesel 1 | + |  |  |  |  |  |  |  |  |  |  |  |  | + |
| Diesel 2 | + |  |  |  |  |  |  |  |  |  |  |  | + | + |
| No. 2 | + |  |  |  |  |  |  |  |  |  |  |  | – | + |
| HSFO | + |  |  |  |  |  |  |  |  |  |  |  |  | + |
| LSFO | + |  |  |  |  |  |  |  |  |  |  |  |  | + |
| Other | + |  |  |  |  |  |  |  |  |  |  |  |  | + |
| KWH | + |  |  |  |  |  |  |  |  |  |  |  | + | + |
| BTU | + |  |  |  |  |  |  |  |  |  |  |  | + | + |
| Op. Cost | + |  |  |  |  |  |  |  |  |  |  |  | + | + |
| Invest |  |  |  |  |  |  |  |  |  |  |  |  | + | + |

Figure 3. Refining Industry Model — Refinery Matrix for One District

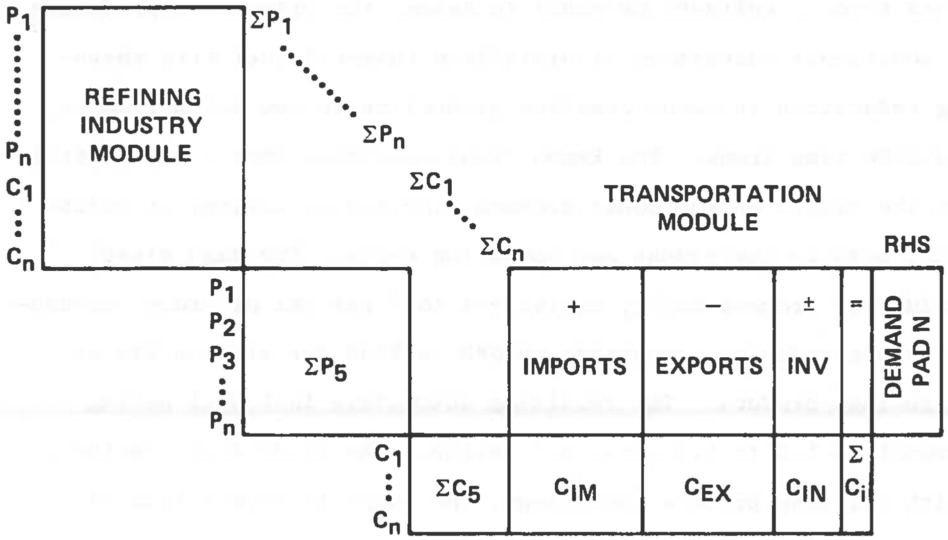

Figure 4. Refining Industry Model— Conceptual Matrix for One District

diesel engine. Another efficiency move proposed is to increase the mandated octane level of lead-free gasoline to permit increase compression ratios in gasoline engines. Desulfurization of gasoline has been proposed to alleviate the sulfates emission problem associated with the catalytic converter. In fact, the possibility of mandated sulfur removal from all transportation fuels has been raised. Each of these changes would require some modifications in refinery operations and/or refinery facilities. The required refinery modifications could, in turn, influence the timing, cost, feasible extent, and net benefit of the changes in fuel characteristics. The industry model is to be used to provide quantitative estimates of these factors.

Since the potential impact of these proposals is profound in terms of additional capital required in the refining industry, it is not surprising that studies have been conducted to assess the cost/benefit effects. The gasoline/diesel ratio shift was studied by Exxon under sponsorship of the EPA and the results published in July 1974. The study used Exxon's refinery LP model to assess the effects of producing various additional quantities of distillate (diesel) fuel with corresponding reductions in motor gasoline production in new refineries in the 1990-2000 time frame. The Exxon study concludes that a substantial shift to the diesel engine could produce significant savings in refining costs, both in investment and operating costs. The high diesel case could save process energy equivalent to 2 percent of crude throughput and reduce refining investment by $83 to $108 per million Btu of automotive fuel product. The resulting automotive fuel cost saving could amount to 1.3 to 1.5 cents per gallon. The study also concludes that, with existing process technology, the complete elimination of gasoline production is not feasible.

The issue of optimal lead-free gasoline octane number is also of widespread interest as it relates to automobile efficiency. The availability of higher octane gasoline allows the use of higher compression ratios in engine design, with the corresponding higher fuel efficiency. When the EPA mandated the availability of a lead-free gasoline to accommodate the catalytic converter, the octane requirement was set at 91 RON, minimum. This octane level was about equivalent to the quality of the existing premium gasoline without the lead additive. At this octane level, the allowable engine compression ratio for knock-free performance is about 8:1, as compared to over 10:1 for the 100 RON premium gasoline engine. From the refiner's viewpoint, higher octane lead-free gasoline production requires more severe processing, which consumes more energy. Thus, from a national energy consumption viewpoint, a trade-off exists between automotive efficiency gained from higher octanes versus reduced refining efficiency. In a recent article (Oil and Gas Journal, September 29, 1975) by Brown, et al. of Exxon, a study of this trade-off was presented. The study was conducted using LP models of three existing refineries and one hypothetical refinery. The major conclusions of the Exxon study are:

(1) Energy savings equivalent to 1 to 3 percent of crude oil are possible with an octane number increase of 3 to 4 units.

(2) Effective costs of crude oil saved range from $18 to $30 per barrel.

(3) Increased compression ratios are not economical relative to current prices of imported or new domestic crude oil.

In each of the studies quoted here the refining industry impact was assessed with the use of refinery LP model case studies. Other industry studies, such as the Bonner and Moore studies on gasoline lead removal, have used a similar approach. Although this approach appears to provide a reasonably rigorous evaluation of the refinery effects, there remains the potential problem that the factors external to the refinery may not be explicitly considered in the modeling effort. For example, optimized refineries may require more of a given type of crude oil than the delivery pipeline can provide. Or, the aggregated requirements of a given feedstock as calculated by the case study approach may exceed the actual availability.

The refining industry model being developed in this project, as described previously, includes explicit treatment of elements of the industry both external and internal to the refinery sector. It is thus expected that a better understanding and analysis of impacts on the refining industry will result from the application of this model.

# EVALUATION OF LITHIUM/SULFUR BATTERIES FOR AUTOMOBILES

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## ABSTRACT

A Li-Al/FeS battery (60 kW, 42 KW-hr, 350 kg) was designed for installation under the hood of a compact car (3400 lb) having a range of about 100 miles. Calculations showed that this battery could be recharged at home in about five hours and recharged at a recharging station in one to two hours. A Li-Al/$FeS_2$ cell having a capacity of about 100 amp-hr and weighing 1.8 kg is being tested on a computer-controlled cycling system that simulates the power requirements for automobile driving conditions. On the SAE-J227 driving profile and a maximum power draw of 45 watts, the cell completed 275 driving cycles in a single discharge of 67.5 amp-hr. The performance projected for improvements in the cells which are now underway indicates that the calculated performance required for the automobile battery are obtainable with the lithium aluminum/metal-sulfide system.

# HIGHWAY VEHICLE RETROFIT EVALUATION

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## ABSTRACT

This paper discusses the current status of engine and chassis dynomometer tests and significant results to date. Over 20 representative classes of retrofit devices/ concepts/techniques, including over 130 specific items, were examined in Phase I of this study. The specturm of devices examined include: carburetors; acoustic and mechanical atomizers; lean-bleed devices; vapor injectors; fuel modifications; inlet manifolds; ignition systems; drivetrain components; drag reduction techniques; driver aids; cooling fans; valve timing modifications; tuneups; compression ratio increases; exhaust-related systems; and engine oils, oil additives, and filters.

Several devices were selected for testing in Phase II of the program. These devices (a) were considered to have the potential for fuel economy improvement of 5 percent or more, (b) required additional confirmatory testing to adequately establish their fuel economy improvement potential, and (c) were available and within the scope of Phase II efforts insofar as tests with and without the device were considered sufficient to establish their relative merit. These devices included: Dresserator carburetor, Ultrasonic Fuel System carburetor, Edelbrock and Offenhauser high-velocity intake manifolds, Hooker and Hedman turned exhaust systems, MSD capacitive discharge ignition system, and the combination of intake manifold plus tuned exhaust system.

## DISCUSSION

### 1. Summary of Phase I Results

A very brief summary of the highlights of the Phase I analysis and preliminary evaluation is presented in Table 1 to give a basis of perspective to the Phase II results presented herein. The basic classes of devices are listed in the left-hand column of the figure. Each such class was evaluated as to fuel economy improvement potential in the four categories shown:

a. Negative (- to 0%)
b. Negligible (0 to 4%)
c. Modest (5 to 14%)
d. Substantial (15% and above)

These ratings were based upon available test data plus analyses of the general operational principles of a given device and its possible effects on spark ignition engine operation in order to substantiate or explain the test data.

Carburetors providing improved fuel atomization and/or lean operation were rated in the "modest" category; two such carburetors were selected for Phase II tests.

Below-carburetor atomizers of the screen type were judged to have a "negligible" effect, while acoustic atomizers were rated in the "modest" category. The Post Carburetor Atomizer (PCA) was initially selected for Phase II tests, but dropped when it was not available for the engine selected for Phase II evaluations.

Lean-bleed systems were placed in the "negligible" category, although it was realized that some pre-controlled cars with richer air-fuel ratios could have a "modest" increase in fuel economy.

Vapor injectors, fuel additives, fuel mixtures, and fuel pressure regulators were rated in the "negligible" column.

The inlet manifold test data were somewhat mixed, with Edelbrock data indicating gains in the "modest" category. Both Offenhauser and Edelbrock inlet manifolds were selected for Phase II tests.

## TABLE 1. COMPARISON OF CONCEPTS/DEVICES — FUEL ECONOMY POTENTIAL

| CLASS/DEVICE | FUEL ECONOMY IMPROVEMENT POTENTIAL* | | | |
|---|---|---|---|---|
| | NEGATIVE - TO 0% | NEGLIGIBLE 0 TO 4% | MODEST 5 TO 14% | SUBSTANTIAL 15% AND ABOVE |
| CARBURETORS (selected ones) | | | X | |
| ATOMIZERS | | SCREENS | ACOUSTIC PCA | |
| LEAN-BLEED SYSTEMS | | X | SOME PRE-CONTROLLED CARS COULD HAVE MODEST INCREASE | |
| VAPOR INJECTORS | | X | | |
| FUEL MODIFICATIONS | | | | |
| FUEL ADDITIVES | | X | | |
| FUEL MIXTURES | | X | | |
| INLET MANIFOLDS | | OFFENHAUSER DATA | EDELBROCK DATA | |
| PRESSURE REGULATORS | | X | | |
| FUEL PRE-AGITATOR | X | | | |
| IGNITION SYSTEMS | | | | |
| CAPACITIVE DISCHARGE | | ON MAINTAINED VEHICLES | ON CARS WITH LEAN AIR-FUEL RATIOS | |
| ELECTRONIC INDUCTIVE | | ON MAINTAINED VEHICLES | ON CARS WITH LEAN AIR-FUEL RATIOS | |
| OTHERS | | X | | |
| EMISSION CONTROL RETROFITS | X | | | |
| DRIVETRAIN | | | | |
| TIRES | | | RADIAL TIRES | |
| TRANSMISSIONS | | | TRUCK AUTOMATIC TRANSMISSIONS | |
| REAR AXLE GEAR RATIOS | | | X | HIGHWAY DRIVING |
| OVERDRIVE UNITS | | | X | HIGHWAY DRIVING |
| DRAG REDUCTION DEVICES | | X | HIGHWAY DRIVING | |
| DRIVER AIDS | | ← | INDETERMINATE | → |
| FLEXIBLE COOLING FANS | | X | | |
| VALVE TIMING | | X | | |
| TUNEUPS | | | X | |
| COMPRESSION RATIO INCREASE | | | X - NOT RECOMMENDED | |
| TUNED EXHAUST SYSTEMS | | | X | |
| DUAL EXHAUST SYSTEMS | | X | | |
| EXHAUST CUTOUT | | | X - NOT RECOMMENDED ILLEGAL IN SOME STATES | |
| TURBOCHARGERS | X - WITH SAME ENG | | | WITH REDUCED ENG CID |
| ENGINE OIL | | | MAY BE POSSIBLE | |
| ENGINE OIL ADDITIVES | | | MAY BE POSSIBLE | |
| ENGINE OIL FILTER | | X** | | |
| TAMPERING WITH ECSs | ← X | → | | |
| SUGGESTED COMBINATIONS | | | | |
| INLET MANIFOLD AND TUNED EXHAUST | | | X | POSSIBLE |
| CARBURETOR PLUS CD IGNITION - MSD, IN PARTICULAR | | | X - LEAN AIR FUEL RATIOS | |

* Based on present state of the art and available data

** Prevents performance degradation over lifetime

Capacitive and inductive high energy ignition systems were judged to have "negligible" effects on maintained vehicles, but it was also felt that cars with leaner air-fuel ratios could obtain "modest" benefits. A capacitive discharge system, the multiple spark (MSD) system, was selected for Phase II testing.

Radial tires, new 4 and 5 speed truck automatic transmissions, lower rear axle ratios, and overdrive units were rated in the modest category. Both overdrives and axle ratio changes can result in substantial improvements during highway driving alone. In all cases, the available data was considered sufficient for evaluation purposes.

Drag reduction devices were rated in the "negligible" category for city and mixed driving and in the "modest" category for highway driving. Tests of these devices were beyond the scope of Phase II activities.

The fuel improvement potential of driver aid devices was judged to be indeterminate based on data acquired in Phase I.

Flexible cooling fans and valve timing modifications were rated in the "negligible" category.

The improvement due to tuneups was rated in the "modest" category. The activities required to more accurately quantify such effects were beyond the scope of Phase II.

Although it was recognized that compression ratio increases could result in "modest" improvements, they were not recommended because of possible emissions effects and increased octane requirements.

Tuned exhaust systems were rated in the "modest" category and were selected for Phase II testing. Dual exhaust systems were judged to have negligible effects; exhaust cutouts, which could provide a "modest" improvement, were not recommended because of noise and illegality in some states.

Turbochargers require an engine change to a smaller displacement (CID) in order to achieve meaningful fuel economy improvements. The available data are adequate for evaluation purposes.

Engine oils, and oil additives were felt to have "negligible" effects on fuel economy, based on the data on hand. However, it was recognized that "modest" benefits may be possible with improved formulations. The type and amount of testing required to quantify such benefits were beyond the scope of Phase II efforts.

Finally, our analyses and available data suggested that two combinations also appeared attractive. They were the inlet manifold plus tuned exhaust and high energy ignition plus lean air-fuel ratios. These combinations were selected for Phase II evaluation.

## 2. Overview of Phase II Program

An overview of the Phase II test program is shown in Table 2. The test program is divided into two parts. In the first part, individual and combined devices were tested on a 1973 350 CID Chevrolet engine at steady-state test conditions on an engine dynamometer at the University of Michigan Automotive Engineering Laboratory. In the second part, promising devices from the University of Michigan test program, plus two carburetor systems, were to be tested on a chassis dynamometer in a 1973 Chevrolet Impala with a 350 CID engine. The Dresser carburetor is still in the development status, and not available for testing as yet.

The remaining sections present the test results to date, by device category.

## 3. Intake Manifold Tests

Figure 1 illustrates the Edelbrock Streetmaster intake manifold. Its principal features embody high flow velocities to obtain improved fuel-air mixing and distribution. The available data in the popular press indicated fuel economy improvements up to 20 percent. However, the basis for the claims, in terms of test type and data control, was not adequately defined.

Figure 2 shows the results of steady-state engine dynamometer tests with this device. The data is shown as a function of the steady-state

TABLE 2. OVERVIEW OF PHASE II TEST PROGRAM PLAN

| UNIVERSITY OF MICHIGAN<br>ANN ARBOR, MICHIGAN | FACILITY | OLSON LABORATORIES<br>ANAHEIM, CALIFORNIA AND LIVONIA, MICHIGAN |
|---|---|---|
| STEADY STATE - ENGINE DYNO | TEST MODE | 1975 FTP - CHASSIS DYNO |
| DEVICE | RETROFIT TEST DEVICES | DEVICE |
| o Multiple Spark Discharge (MSD) System<br>o High Performance Intake Manifold<br>Edelbrock Streetmaster<br>Offenhauser Dual Port<br>o Tuned Exhaust Headers<br>Hooker<br>Hedman<br>o Combined H. P. Intake Manifold Plus Tuned Exhaust Headers | | o Dresserator Inductor<br>o Ultrasonic Fuel Induction System (A. K. Thatcher, Merritt Island, Fla.)<br>o Promising Devices from University of Michigan Screening Test Program |

VIEW OF THE EDELBROCK STREETMASTER INLET MANIFOLD

- FEATURES
  - SINGLE-PLANE, LARGE PLENUM
  - ALL BRANCHES EMERGE RADIALLY FROM CENTRAL CAVITY
  - REDUCED CROSS-SECTIONAL AREAS
    - OBTAIN HIGH FLOW VELOCITY
- CLAIMS
  - IMPROVED FUEL ECONOMY
    - UP TO 20% IN RECREATIONAL VEHICLES
    - REDUCED EMISSIONS
- COST FACTORS
  - HARDWARE, $135 TO $165
  - INSTALLATION TIME, 2 TO 6 hr

Figure 1. Inlet Manifolds — Edelbrock

road-load speed condition. The vertical scale is the change in BSFC over baseline tests without the device installed. Percent decreases in BSFC, above the 0 or base line, therefore represent areas of fuel economy improvement.

This is a two-venturi (2-V) carburetor configuration. As can be noted, 14 to 15 percent improvements were obtained in the 25-35 mph range, with essentially no change at other speed conditions. Wide-open throttle (WOT) tests at 25 and 55 mph show a reversed trend, with the largest gain (approximately 5 percent) at 55 mph.

The Edelbrock and the Offenhauser Dual Port manifolds were tested in the four-venturi (4-V) configuration, as shown in the Figure 3. The Offenhauser unit was available only as a 4-V unit.

Here, the general trends of the two units are nearly reversed, or mirror images. The Edelbrock unit has a small improvement at 25 mph and small losses in fuel economy over the rest of the speed range. The Offenhauser unit has a loss at 25 mph and slight gains over the rest of the speed range. At wide-open throttle conditions, significant improvements at 55 mph were noted for both units.

These general trends were not considered to imply significant improvements over the stock 4-V manifold configuration. Therefore, the 2-V Edelbrock manifold was tested in the 1973 Chevrolet Impala on a chassis dynamometer with the results shown in Table 3.

In terms of the FTP or EPA Certification Test Procedure, the use of the Edelbrock intake manifold resulted in a 5 percent loss in fuel economy over the stock baseline configuration. On the Highway Driving Cycle, the Edelbrock registered nearly a 7 percent gain in fuel economy. During steady-state driving conditions, the Edelbrock had a 1.5 percent improvement at 35 mph, and a 4.8 percent improvement at 55 mph. These results are contrary to the engine dynamometer steady-state trends, but are fairly consistent with the WOT trends obtained on the engine dynamometer.

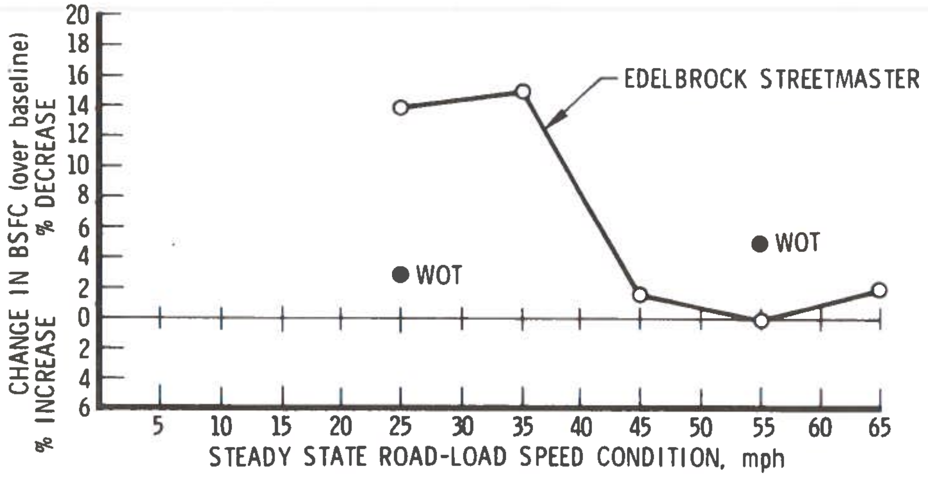


Figure 2. Intake Manifold Test Results – 2-V Configuration, University of Michigan Engine Dynamometer Tests

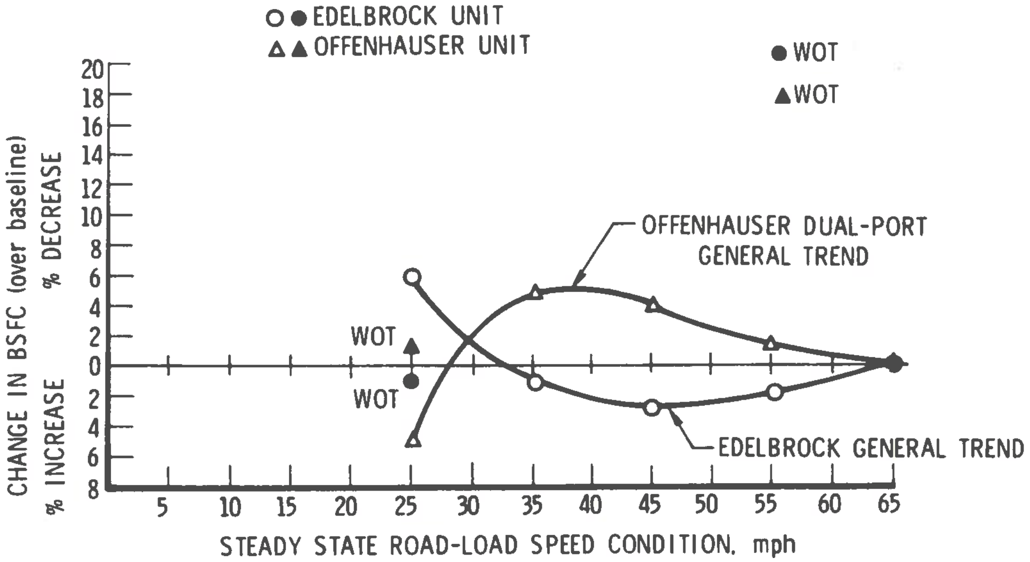


Figure 3. Intake Manifold Test Results – 4-V Configuration, University of Michigan Dynamometer Tests

With regard to the FTP results, it would appear that steady-state engine dynamometer results are not useful in the predictive sense, due to the dominance of cold-start effects, accelerations, and idling periods inherent in the FTP driving cycle.

Table 4 shows the emissions test results on the FTP. Although there was a 5 percent loss in fuel economy (Table 3), there were significant reductions in both HC and CO, with no change in $NO_x$.

## 4. Tuned Exhaust System Tests

Figure 4 illustrates the next device tested, the tuned exhaust system, where pipes from each exhaust port are merged into a common collector tube. Pressure waves created in the exhaust pipe are reflected back as suction waves toward still-open exhaust valves, thus exerting an evacuating effect on gases still in the cylinder, if the pipe is "tuned" or has the correct length. Again, the available data in the popular press had indicated sizable fuel economy improvements for such systems, but with a lack of definition of testing methods and accuracy.

Figure 5 depicts engine dynamometer test results. The ordinates here are the same as shown previously for the Edelbrock inlet manifold.

Both Hooker and Hedman tuned exhaust systems showed very similar trends: poorer fuel economy at steady-state speeds below 50 mph. Small improvements of 2 to 3 percent are indicated above 50 mph. At WOT conditions, 4 to 5 percent increases are shown for 55 mph.

Chassis dynamometer tests have not yet been conducted. However, we have tested the combination of the Hooker tuned exhaust system and the Edelbrock inlet manifold on the engine dynamometer, as shown in Figure 6.

Here, the combined systems showed a measurable and consistently beneficial fuel economy trend across the speed range. This specific configuration is currently installed in the 1973 Chevrolet Impala at Olson Laboratories in Livonia, Michigan, with results expected by November 10, 1975.

## TABLE 3. FUEL ECONOMY TEST RESULTS — EDELBROCK 2-V INTAKE MANIFOLD — 1973 CHEVROLET IMPALA, 350 CID ENGINE

| CONFIGURATION | FTP FUEL ECONOMY MPG[1] | HIGHWAY FUEL ECONOMY MPG[1] | STEADY-STATE FUEL ECONOMY, MPG[1] | |
|---|---|---|---|---|
| | | | 35 MPH | 55 MPH |
| BASELINE VEHICLE | 11.25 | 16.58 | 19.19 | 16.81 |
| EDELBROCK INTAKE MANIFOLD | 10.69<br>(-5.0)[2] | 17.71<br>(+6.85)[2] | 19.48<br>(+1.5)[2] | 17.62<br>(+4.8)[2] |

(1)Average of 2 tests

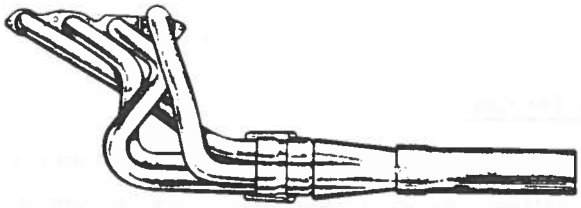
(2)Numbers in parentheses represent percent change over baseline case.

## TABLE 4. EMISSION TEST RESULTS — EDELBROCK 2-V INTAKE MANIFOLD — 1973 CHEVROLET IMPALA, 350 CID ENGINE

| CONFIGURATION | FTP COMPOSITE EMISSIONS, GRAM/MI[1] | | |
|---|---|---|---|
| | HC | CO | $NO_x$ |
| BASELINE VEHICLE | 2.65 | 37.60 | 3.02 |
| EDELBROCK INTAKE MANIFOLD | 1.87<br>(-30) (2) | 27.07<br>(-28) (2) | 3.02<br>( 0 ) (2) |

(1)Average of 2 tests

(2)Numbers in parentheses represent percent change over baseline case.



- TUNED EXHAUST SYSTEMS
  - REDUCE EXHAUST BACK-PRESSURE
  - IMPROVE FUEL ECONOMY
  - PIPES CONNECTED TO EXHAUST PORT OF EACH CYLINDER MERGED INTO COMMON COLLECTOR
  - OPERATION
    - PRESSURE WAVE CREATED IN EXHAUST PIPE AT BEGINNING OF OPENING OF EXHAUST VALVE AND DISCHARGE OF EXHAUST GASES
    - WAVE PROPAGATES THROUGH PIPE WITH SONIC VELOCITY
    - REFLECTED BACK AS A SUCTION WAVE TOWARDS STILL-OPEN EXHAUST VALVE
    - AT VALVE, SUCTION WAVE EXERTS EVACUATING EFFECT ON GASES STILL IN CYLINDER
      - IF PIPE IS TUNED (has correct length)
  - HIGH ENGINE SPEEDS
    - POWER OUTPUT INCREASED DUE TO CYLINDER SCAVENGING (volumetric efficiency)
  - LOW AND MEDIUM ENGINE SPEEDS
    - REDUCED PUMPING LOSSES AND IMPROVED FUEL ECONOMY
  - MULTI-CYLINDER EFFECTS
    - INTERFERENCE EFFECTS AT COMMON COLLECTOR CAN STRONGLY INFLUENCE BASIC CHARACTERISTICS

Figure 4. Exhaust-Related Systems

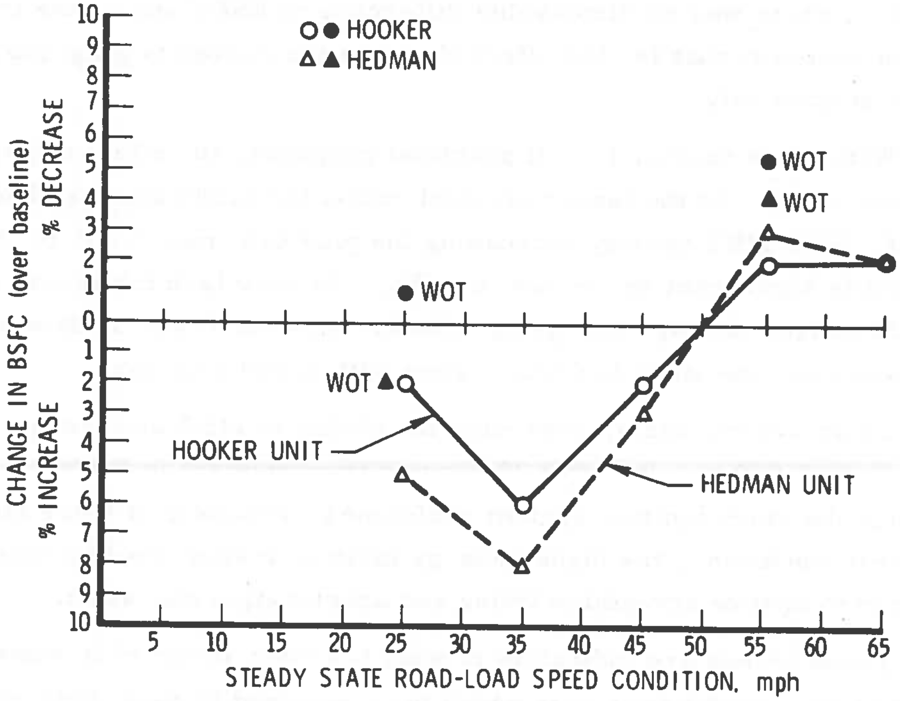


Figure 5. Tuned Exhaust Header Test Results — 2 V Configuration, University of Michigan Dynamometer Tests

## 5. MSD-2 Device

Figure 7 represents similar engine dynamometer test data for the MSD-2, capacitive, multiple spark discharge ignition system. As we predicted in Phase I, rounded to the nearest percent, the gains are minimal and in the order of 1 percent. This was a test at stock engine air-fuel ratio and timing. The only change was the substitution of the MSD for the stock ignition system.

## 6. Air-Fuel Ratio and Plug Gap Effects

Additional tests were made at 35 and 55 mph steady-state road-load conditions to indicate possible effects at lean air-fuel ratios and advanced timing.

Figure 8 illustrates the results at 35 mph conditions. Three ignition systems, stock, MSD, MRI, and 3 spark plug gap settings were employed at both stock timing conditions and MBT timing. Except where indicated, there was no displayable difference in BSFC among the three ignition systems; that is, the effect shown in the curves is plug-gap and timing-related only.

With stock timing, for all practical purposes, the effect of plug gap was also small. At the leaner air-fuel ratios the 0.080 plug gap had some benefit. With MBT timing, increasing the plug gap from 0.035 to .060-.080 resulted in significant decreases in BSFC. At very lean mixtures, in the 17 to 20 range, the high energy ignition systems (MSD and MRI) were improved over the stock ignition system with 0.060 plug gap.

On an overall basis, advancing the timing to MBT and increasing plug gap to 0.060 resulted in a 20 percent improvement in BSFC. Although the stock ignition system performed adequately at these steady-state test conditions, the higher energy ignition system would probably be required to assure acceptable idling and acceleration operation.

These trends are indicative of what has been achieved in some 1975 and 1976 model year cars which have returned to near-MBT timing

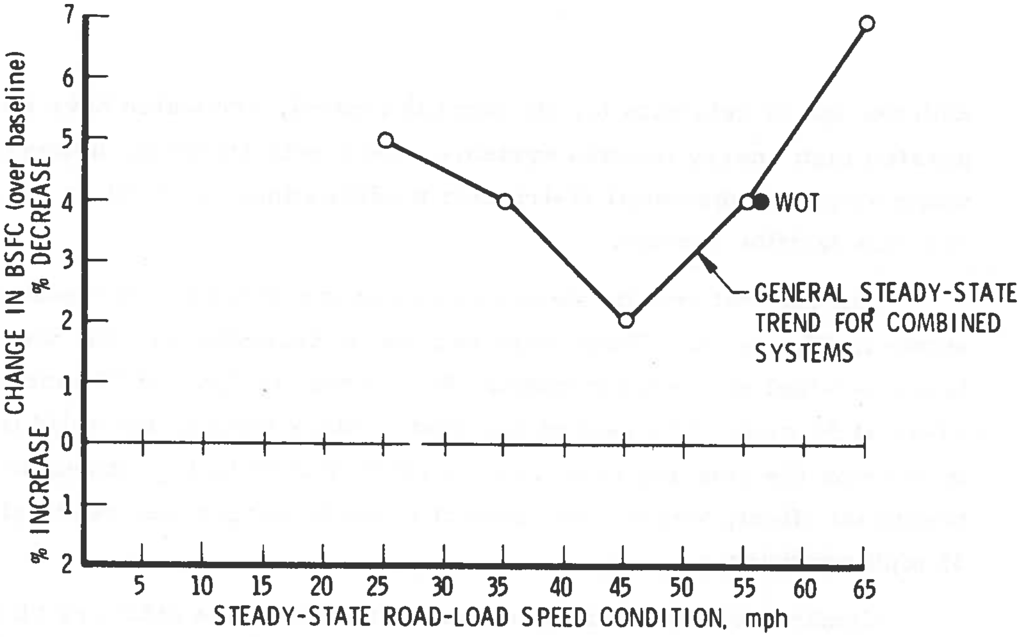


Figure 6. Test Results — Edelbrock Manifold Plus Hooker Tuned Exhaust — 2-V Configuration, University of Michigan Engine Dynamometer Tests

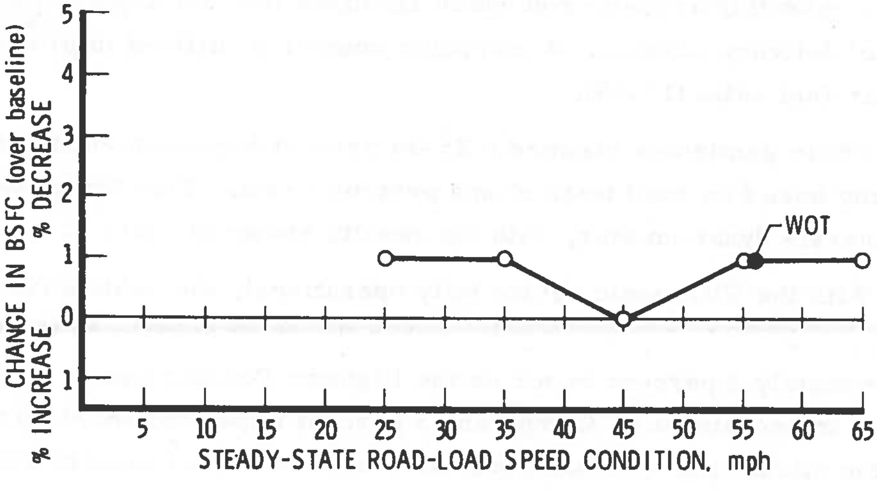


Figure 7. Test Results — MSD-2 Ignition System — 2-V Configuration, University of Michigan Engine Dynamometer Tests

with the use of catalysts for HC and CO control, and which have incorporated high energy ignition systems. On a retrofit basis, however, this would require substantial distributor modifications, as well as the addition of a new ignition system.

Similar test results were obtained at the 55 mph test condition, as shown in Figure 9. There were two major differences. One was a shift in the air-fuel ratios for minimum BSFC from 16-16.5 at 35 mph to 17-18 at 55 mph. The second was that at stock timing, the solid lines, increasing the plug gap from .035 to .060 or .080 had a noticeable beneficial effect, whereas the impact of such changes was minimal at the 35 mph condition.

Confirmatory chassis dynamometer tests of the MSD are planned to quantify the effects of cold start, acceleration, and idling conditions on fuel economy.

### 7. Ultrasonic Fuel System Tests

Figure 10 depicts the essential features of the Ultrasonic Fuel System, invented by A. K. Thatcher and E. McCarter of Orlando, Florida. It has a vibrating acoustic rod which atomizes the fuel impinged upon it by two fuel delivery nozzles. A computer control is utilized to provide a fixed lean air-fuel ratio (17-18).

These gentlemen claimed a 25-30 percent improvement in fuel economy based on road tests of one prototype unit. This device was tested on a chassis dynamometer, with the results shown in Table 5.

With the Ultrasonic device fully operational, the vehicle fuel economy was approximately 3 percent poorer than the stock vehicle on the FTP, and approximately 2 percent better on the Highway Driving Cycle. It had a 6 percent improvement at 35 mph and 3 percent improvement at 55 mph. With the ultrasound disconnected, the results were not greatly different, however, except at 55 mph conditions.

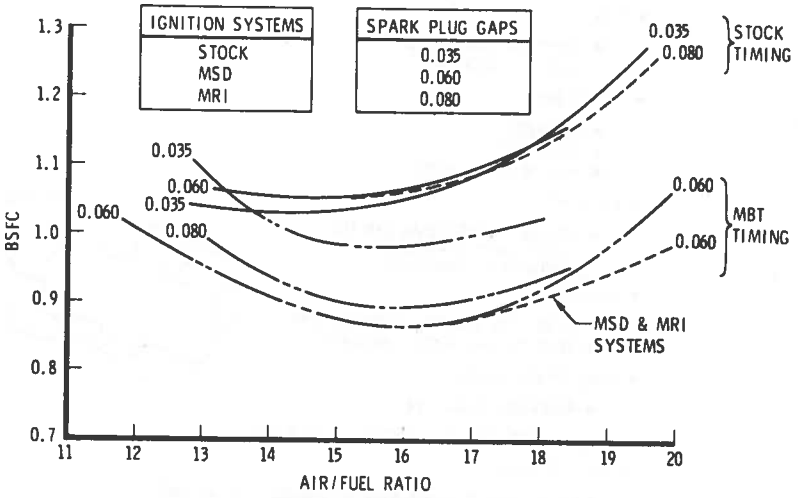


Figure 8. Air/Fuel Ratio and Plug Gap Effects — 35 Mph Steady-State Road-Load Conditions, University of Michigan Engine Dynamometer Tests

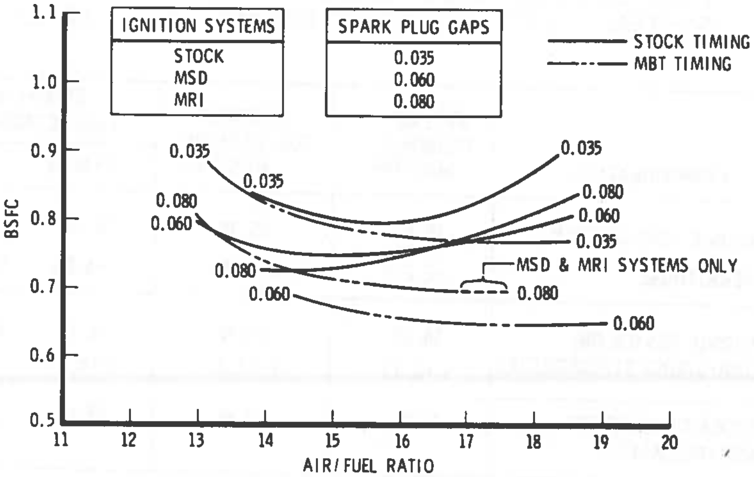


Figure 9. Air/Fuel Ratio and Plug Gap Effects — 55 Mph Steady-State Road-Load Conditions, University of Michigan Engine Dynamometer Tests

- TYPE
  - COMPUTER-CONTROLLED ACOUSTIC ATOMIZER
- COMPONENTS
  - ATOMIZER
  - COMPUTER
  - FUEL METERING PUMP
- APPROACH
  - DELIVER A FIXED, LEAN AIR-FUEL RATIO OVER A RANGE OF OPERATING CONDITIONS
- CLAIMS
  - 25-30% FUEL ECONOMY IMPROVEMENT
  - MEET 1975 EMISSION STANDARDS
- DEVELOPMENT STATUS
  - RESEARCH PROTOTYPE
    - ONE TEST UNIT PRESENTLY ON A CAR
- COST FACTORS
  - INVENTORS ESTIMATE MANUFACTURING COST AT ~ $50

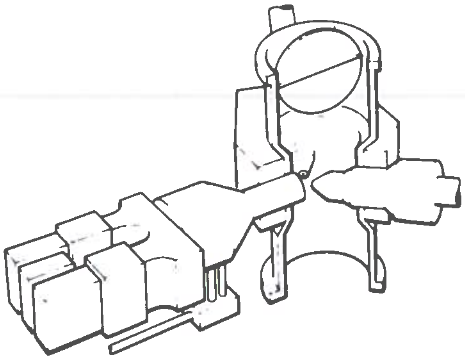


Figure 10. Ultrasonic Fuel System — A.K. Thatcher and E. McCarter

TABLE 5. FUEL ECONOMY TEST RESULTS -- ULTRASONIC FUEL INDUCTION SYSTEM — 1972 PLYMOUTH DUSTER, 225 CID ENGINE

| CONFIGURATION | FTP FUEL ECONOMY MPG(3)(4) | HIGHWAY FUEL ECONOMY MPG(3)(4) | STEADY-STATE FUEL ECONOMY, MPG(3)(4) | |
|---|---|---|---|---|
| | | | 35 MPH | 55 MPH |
| ULTRASONIC DEVICE FULLY OPERATIONAL(1) | 15.66<br>( -2.7 ) | 25.32<br>( +1.8 ) | 30.87<br>( +6.0 ) | 26.64<br>( +3.2 ) |
| ULTRASONIC DEVICE ON; ULTRA-SOUND DISCONNECTED | 16.18<br>( +0.6 ) | 25.92<br>( + 4.2 ) | 31.12<br>( +6.9 ) | 24.92<br>( -3.4 ) |
| NEW STOCK CARBURETOR; BASELINE CASE(2) | 16.08 | 24.86 | 29.10 | 25.80 |

(1) Computer control set by A. K. Thatcher for A/F ratio in 17.5-18 range.

(2) Standard air/fuel ratio

(3) Numbers in parentheses represent percent change over baseline case.

(4) Average of 2 tests

It is likely that the inventors of this carburetor were misled in their projected fuel economy claims because of the condition of the stock carburetor to which they were comparing their device. Where installed for baseline tests, their stock carburetor was flooding badly and could not be adjusted to give factory settings at idle conditions. Therefore, a new stock carburetor was used for the baseline test data shown in the figure.

The emission test results for the Ultrasonic System are shown in Table 6. With the ultrasonic device operational, there were significant reductions in HC and CO. The $NO_x$ levels were higher, as is often the case for lean air-fuel ratio systems.

## SUMMARY

With regard to overall program status, the Phase I analysis and preliminary evaluation report has been completed and is currently under final review prior to publication.

As noted herein, the engine dynamometer test portion of Phase II has been completed, and a portion of the chassis dynamometer tests made. The remaining chassis dynamometer tests (tuned exhaust system, tuned exhaust plus Edelbrock manifold, MSD ignition system, and MSD plus lean air-fuel ratio) are scheduled for completion by the end of November 1975. At that time, a final evaluation of relative merit will be made.

TABLE 6. EMISSION TEST RESULTS - ULTRASONIC FUEL INDUCTION SYSTEM - 1972 PLYMOUTH DUSTER, 225 CID ENGINE

| CONFIGURATION | FTP COMPOSITE EMISSIONS, GRAM/MI(3)(4) | | |
|---|---|---|---|
| | HC | CO | $NO_x$ |
| ULTRASONIC DEVICE FULLY OPERATIONAL(1) | 1.78<br>( -23.0 ) | 16.02<br>( -35.0 ) | 4.99<br>( +22.0 ) |
| ULTRASONIC DEVICE ON; ULTRASOUND DISCONNECTED | 2.83<br>( +23.0 ) | 31.16<br>( +26.0 ) | 4.64<br>( +13.0 ) |
| NEW STOCK CARBURETOR; BASELINE CASE(2) | 2.31 | 24.72 | 4.09 |

(1) Computer control set by A. K. Thatcher for A/F ratio in 17.5-18 range.

(2) Standard air/fuel ratio

(3) Numbers in parentheses represent percent change over baseline case.

(4) Average of 2 tests

# AUTOMOTIVE MANUFACTURING ASSESSMENT SYSTEM

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## ABSTRACT

Corporate-Tech Planning is developing an Automotive Manufacturing Assessment System (AMAS) to assist TSC analysis in evaluating industry capability to produce fuel efficient vehicles. AMAS will consist of a Master Production Schedule and a computer supported automotive data base. The Master Production Schedule illustrates both the historical and projected introduction of new vehicles, major body and styling changes, new engines and transmissions, technology advancements, and the availability of capital, facilities, tooling, labor, and material. The Master Production Schedule will provide policymakers with a better understanding of the automotive manufacturing process including: lead time and planning cycle durations; strategy and demand forces governing new introductions and changes; and the constraints and limitations on the industry as a whole.

The data base will provide a repository for automotive information by manufacturer including: weight, size and performance data, manufacturing and maintenance costs, capital investment and lead times for tooling and materials, and materials and energy requirements. Using interactive terminals, this system will support both on-line queries and the processing of complex "what-if" scenarios relating to the introduction of fuel efficient vehicles and providing estimates of industry investment requirements and consumer life cycle costs. Work on this project was begun in July 1975 and will conclude in June 1976.

## 1.0 INTRODUCTION

The Automotive Manufacturing Assessment System (AMAS) was started in July 1975 by Corporate-Tech Planning. Its purpose is to provide a computer based system that will assist the Transportation Systems Center in the analysis of industry's capability to produce fuel efficient vehicles. The architecture of the system includes a model of the domestic automotive manufacturing system based on historical data on manufacturing and production of known vehicles for the years 1970 through 1975.

Concurrent with this effort, a Master Production Schedule was also developed to identify lead times and record new auto introductions, styling and body changes of each manufacturer from the present time period out to 1980.

The computer related activities of this program will be described first followed by a description of the Master Production Schedule.

## 2.0 AMAS

The basic features of AMAS are summarized in Figure 1, while Figure 2 illustrates the class of problems AMAS is being designed to service. Figure 3 illustrates the basic structure of the system.

Referring to Figure 3, we see that at the heart of the system is DBMS-10, a data base management system designed to operate on the TSC PDP-10 computer. DBMS-10 will accept the historical data on automotive manufacturing now being collected by Clayton Associates; the service and repair data now being

- A TOOL FOR THE POLICY MAKER
- A UNIQUE DATA BASE OF AUTOMOTIVE MANUFACTURING INFORMATION ON
  - REAL VEHICLES & SUBSYSTEMS
  - ADVANCED TECHNOLOGY
  - MANUFACTURING COSTS, CAPACITIES, CONVERSION LEAD TIMES, ETC.
- ASSISTS IN FINDING ANSWERS TO SIMPLE QUERIES AND COMPLEX "WHAT-IF" QUESTIONS
- CONCEPTS APPLICABLE TO OTHER AREAS OF INTEREST

Figure 1. AMAS – Automotive Manufacturing Assessment System

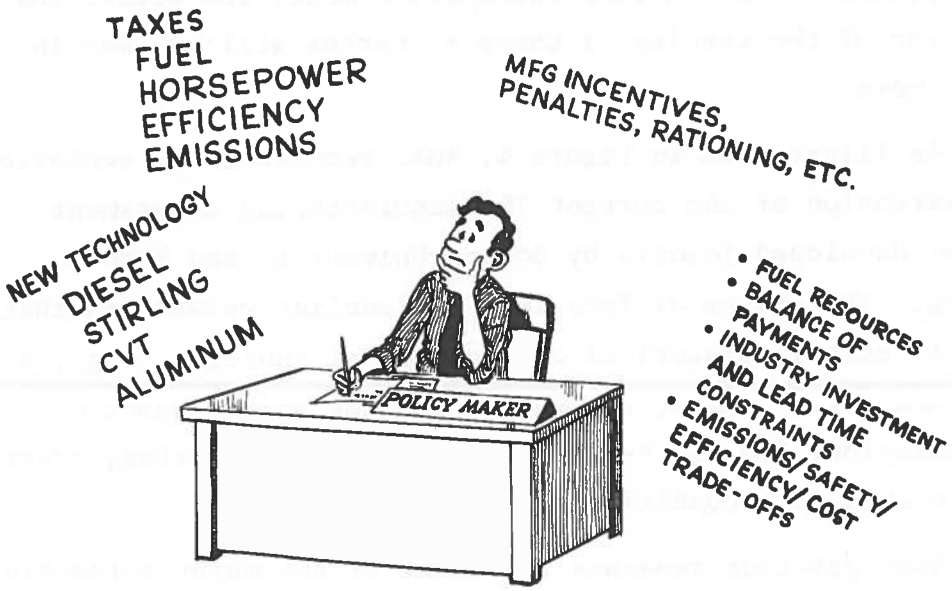


Figure 2. The Problem: To Encourage Production of Fuel-Efficient Vehicles

collected by Arthur D. Little, Inc.; and data on advanced technology relating to vehicles, automotive subsystems, materials, production facilities, etc., presently available in the TSC data base or to be collected in future efforts. These data will be organized by DBMS-10 into an automotive data base which will be accessible in two basic modes. In the first mode of operation, the data base will support terminal inquiries by means of a specially designed automotive query language. This query language, which is now being programmed by Corporate-Tech Planning, will permit analysts at TSC to respond to requests for information from policymakers by interactively interrogating the data base.

In the second mode of access, the data base will be available to answer complex "what-if" questions related to projected vehicle introduction scenarios over a ten-to-twenty year period. The development of these scenarios will be accomplished in an on-line interactive mode; the actual computation of the results of these scenarios will be done in batch mode.

As illustrated in Figure 4, AMAS represents an evolutionary extension of the current TSC manufacturing assessment system developed jointly by Boston University and Rath & Strong. The system differs from the earlier version in that it will contain historical data on actual vehicles (e.g., a 1975 Chevrolet Impala, standard body size with automatic transmission, 350 CID V-8 engine, with power steering, power disk brakes, air conditioning, and four doors).

AMAS provides separate treatment of the major automotive

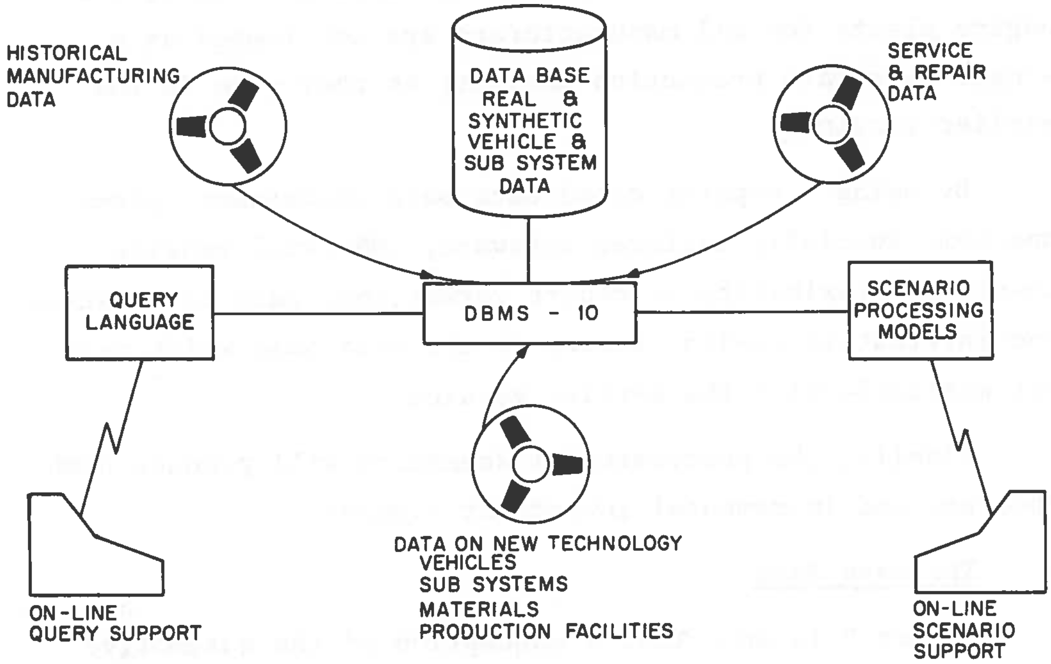


Figure 3. AMAS — Basic System Structure

- HISTORICAL DATA ON REAL VEHICLES & REAL PRODUCTION FACILITIES
- SEPARATE TREATMENT OF MAJOR AUTOMOTIVE MANUFACTURERS
- USES SOPHISTICATED DATA BASE MANAGEMENT SYSTEM
    - FLEXIBILITY IN REPORT FORMATING
    - EASE OF UPDATING
    - ON-LINE ACCESS
- DETERMINES BOTH ABSOLUTE & INCREMENTAL INVESTMENTS

Figure 4. AMAS — An Evolutionary Extension of the B.U./R&S System

manufacturers and their individual facilities. Thus, all engine plants for all manufacturers are not lumped as a single aggregate production facility as they were in the earlier version.

By using a sophisticated data base management system and some specially tailored software, AMAS will provide levels of flexibility in report formatting, ease of updating, and interactive on-line access to the data base which were not available with the earlier version.

Finally, the processing of scenarios will produce both absolute and incremental investment figures.

## A. The Data Base

Figure 5 is an artist's conception of the automotive data base. A data base management system capable of supporting network structured data bases was chosen to accommodate complex relationships which exist within the data now being collected. For example, a bill-of-material type relationship among subsystems is necessary to develop the indented parts list. Furthermore, individual automotive subsystems must be related to the production lines that produce them, the materials required for their production, the labor necessary for their manufacture, etc. To assist the analyst in pursuing the historical development of subsystems, the data base will maintain information on the evolutionary relationships among subsystems.

Because it is likely that data will be collected from multiple sources, all data within the data base will be tagged with source codes so as to assist the analyst in evaluating output and source traceability.

## B. Automotive Natural Data Inquiry

Figure 6 illustrates the type of questions which will be supported by the Automotive Natural Data Inquiry language (ANDI). This facility will permit analysts to generate reports and obtain rapid answers to simple questions. To simplify access to the data base, this query language will employ natural English expressions.

Figure 7 illustrates how the first sample question in Figure 6 is answered by the data base management system. Setting body class to the compact selection and the real/synthetic flag to the real selection, the two data sets are intersected and the set of all real compact vehicles is produced. These, in turn, point to the engine assembly which in turn points to the specific engine subsystem for each of those vehicles where the associated performance data is found. More generic text material is located at the engine type classification (so as to avoid duplication of common data) and this is pointed to from the engine subsystem.

## C. "What-If" Scenarios

Figure 8 graphically illustrates the starting point for the generation of a vehicle introduction scenario. In this case, the analyst has conceived a new vehicle type. Figure 9 illustrates the problem addressed by the "what-if" scenario. Here, we see that the analyst has backed off from the more ambitious vehicle pictured in Figure 8 and is now asking for an evaluation of the introduction of light automotive diesel

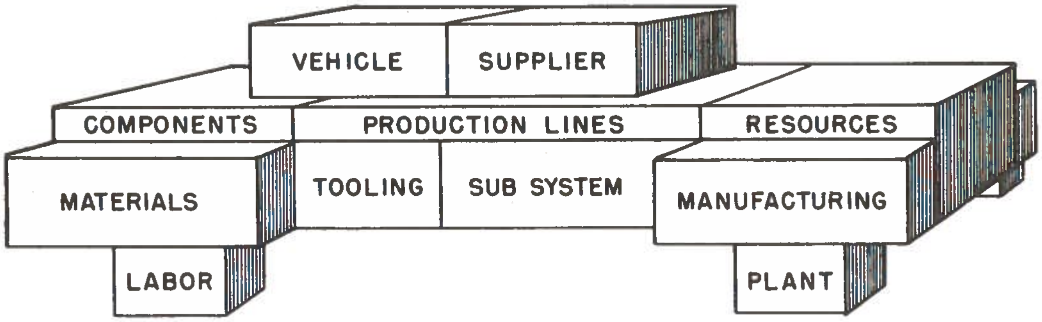


Figure 5. The Data Base

SAMPLE QUERIES

- LIST ALL COMPACT REAL VEHICLES BY MANUFACTURER IN ORDER OF INCREASING WEIGHT AND LIST MANUFACTURER, WEIGHT, MODEL, YEAR, HP, ENGINE TYPE, AND 0 - 60 MPH IN SECONDS.
- FOR THE 1975 FORD TORINO LIST WEIGHT IN LBS BY MATERIAL BY MAJOR ASSEMBLY. LIST MANUFACTURING COST BY MAJOR ASSEMBLY AND INDICATE SOURCE OF DATA.
- LIST IN ORDER OF DECREASING 1975 EMPLOYMENT ALL PLANTS NOW MANUFACTURING 8 CYLINDER GASOLINE ENGINES.

| PLANT NAME | MFG | NO. EMPLOYED | | | PRODUCTION 8-CYL ENG. | | | CONG. DISTRICT |
|---|---|---|---|---|---|---|---|---|
| | | 1973 | 1974 | 1975 | 1973 | 1974 | 1975 | |
| | | | | | | | | |

Figure 6. ANDI — Automotive Natural Data Inquiry

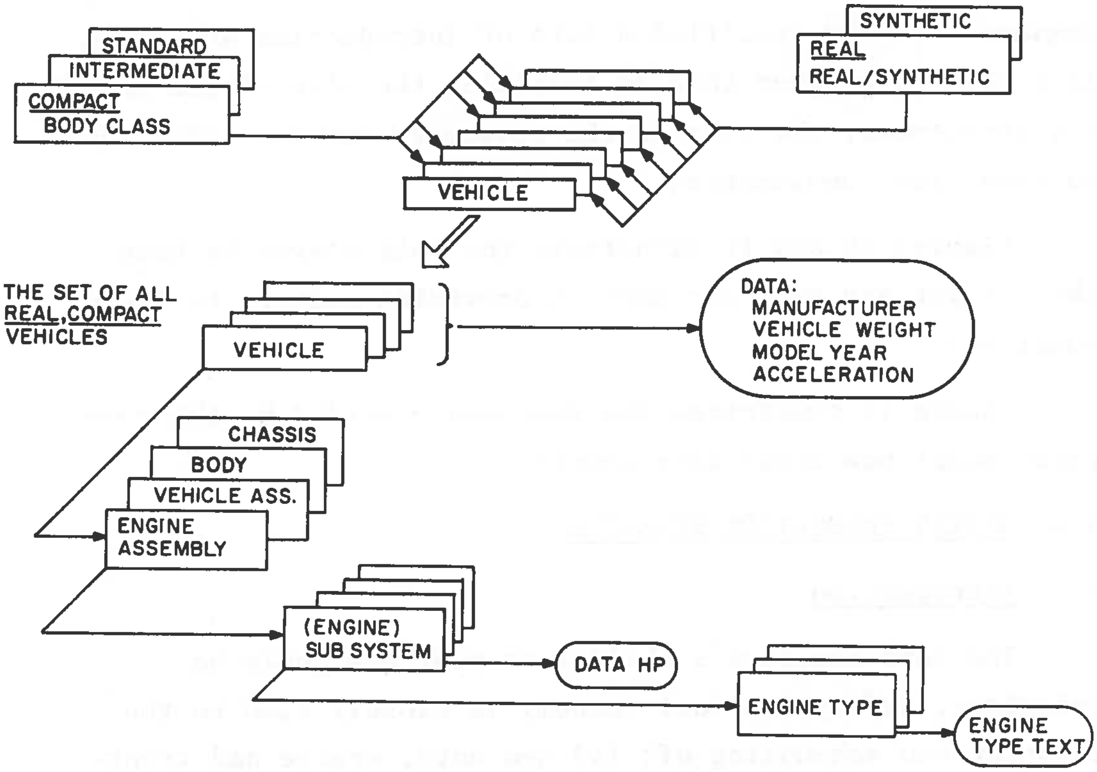


Figure 7. Query Response Using Data Base

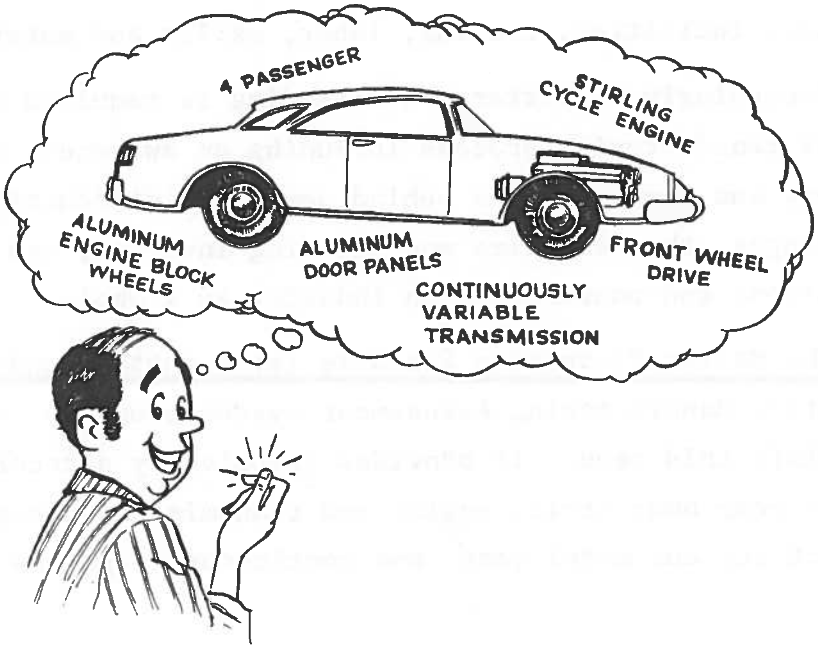


Figure 8. "The Idea"

engines. He has specified a rate of introduction and would like to know whether this is feasible, the size of the industry investment, the cost to the consumer, and the effect on national fuel consumption.

Figures 10 and 11 illustrate the role played by both the analyst and AMAS and ANDI in providing answers to these questions.

Figure 12 summarizes the features provided by the computer model now under development.

## 3.0 MASTER PRODUCTION SCHEDULE

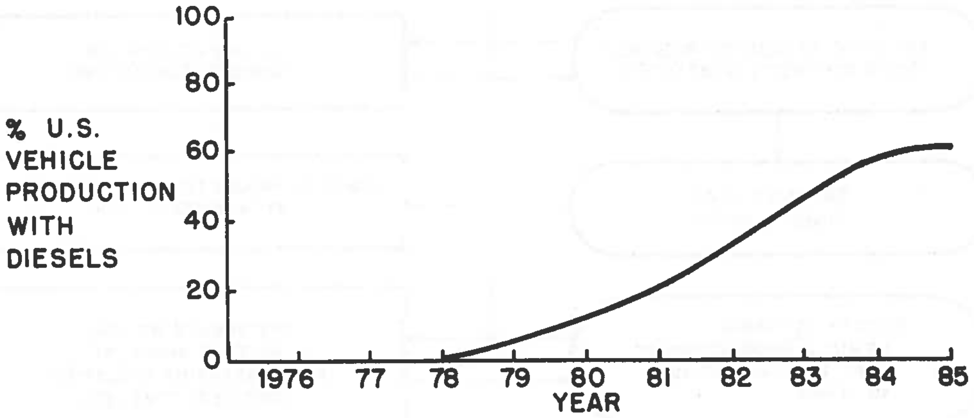
### A. Introduction

The auto industry's ability to meet new goals on emissions, safety and fuel economy is closely tied to the planning and scheduling of: (a) new auto, engine and transmission introductions, (b) major body and styling changes, (c) technology advancements and (d) use of available resources (capital, facilities, tooling, labor, skills and material).

Accordingly, a better understanding is required of the overall manufacturing process including an awareness of the strategy and demand forces behind new auto introductions and changes, the lead time and planning involved, and basic limitations and constraints on industry as a whole.

The Master Production Schedule (as a subtask under the Automotive Manufacturing Assessment System program) is designed to satisfy this need. It provides graphically a record of year-to-year body style, engine and transmission changes by manufacturer and model year, and continuously updates this

RAPID INTRODUCTION OF DIESEL ENGINES ?



- FEASIBLE ?
- INDUSTRY INVESTMENT ?
- LIFE CYCLE COSTS TO CONSUMER ?
- EFFECT ON FUEL CONSUMPTION ?

Figure 9. "What If" Scenarios

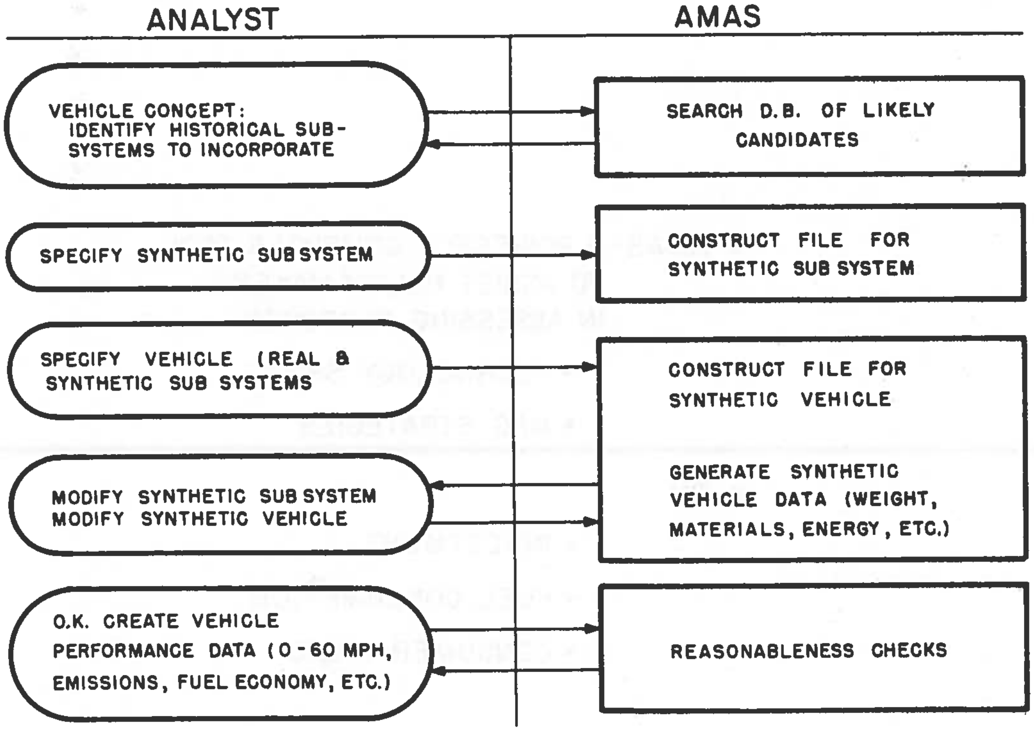


Figure 10. Vehicle Synthesis

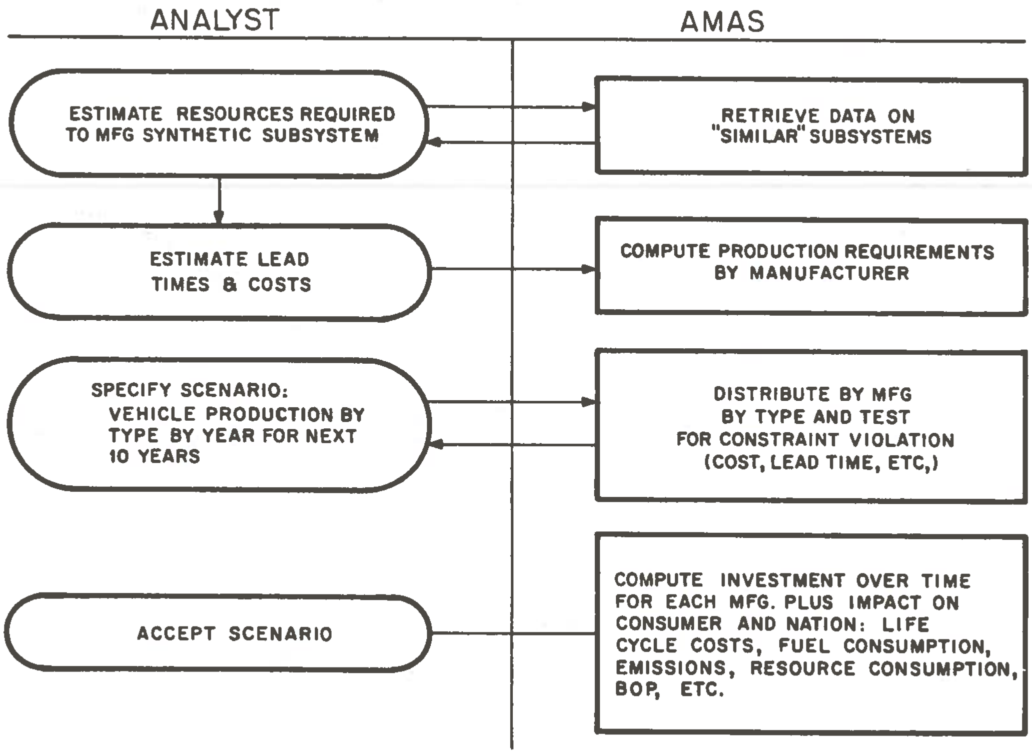


Figure 11. Determine Impact of Vehicle Scenario

- AMAS-A POWERFUL COMPUTER TOOL TO ASSIST POLICY MAKERS IN ASSESSING PROPOSED
  - TECHNOLOGY SHIFTS
  - MFG STRATEGIES
- ON
  - INVESTMENT
  - FUEL CONSUMPTION
  - CONSUMER COSTS

Figure 12. Summary

information with projections to 1980.

The Master Production Schedule also provides basic timing diagrams of the principal development and production phases which aid in the determination of lead time and major milestones required for changes and new introductions of a given model year.

## B. Basic Elements of the Production Schedule

The Production Schedule is primarily a tool for recording and observing changes of a complex picture. As a minimum, it should track changes, additions and deletions of all major model lines, by manufacturer and body size classification. As indicated in Figure 13, the basic changes of interest are those affecting body classes and sizes, styling, power plant, drive trains and emissions. Styling and body class changes are of foremost concern in that these elements are the primary driving force behind all planning and scheduling. Accordingly, the introduction of new engines, transmissions and other items are usually scheduled to coincide with introductions of an all new auto or major body change; and their timing can be projected once the styling schedule is known.

The Master Production Schedule identifies the auto size and body classification in accordance with the six widely used categories: luxury, standard (or regular), intermediate, compact, sub-compact, and mini (the new small car size). Within each size category, vehicles are identified by manufacturer and model (Pontiac-LeMans, Mercury-Marquis, etc.); however, only representative, not all, models are listed.

Styling changes are recorded for each model year accordinto to the degree of change. An all new car or completely new body involves new hard points and is a major resource expenditure; hence, is done sparingly and not on all models in a single year. Once a new model or body has been introduced, it receives little or no change (carry-over) the following year, and then minimal (facelift - new trim, grille, taillight, etc.) changes each succeeding year until the style has run its course.

Power plants are identified by engine types (I-4, L-6, V-8, etc.) and displacement size (cubic inch). Engine changes usually consist of variations in displacement to accommodate power ranges that the yearly body weight and styling changes dictate. An example of new engine introductions is a lightweight diesel or four cylinder engine for the new subcompact and mini classes.

Similarly, changes and additions to transmissions and emission controls are also recorded where technology or major re-tooling impacts scheduling lead time. Examples include changes to: type, or degree of usage, of catalytic converters, fuel metering, five-speed transmission, and lock-up torque converters.

## C. Current and Projected Production Timing

The chart shown in Figure 14 for a representative manufacturer is an example of the Master Production Schedule and illustrates the method for recording and tracking changes of the model and body size classifications as well as engine

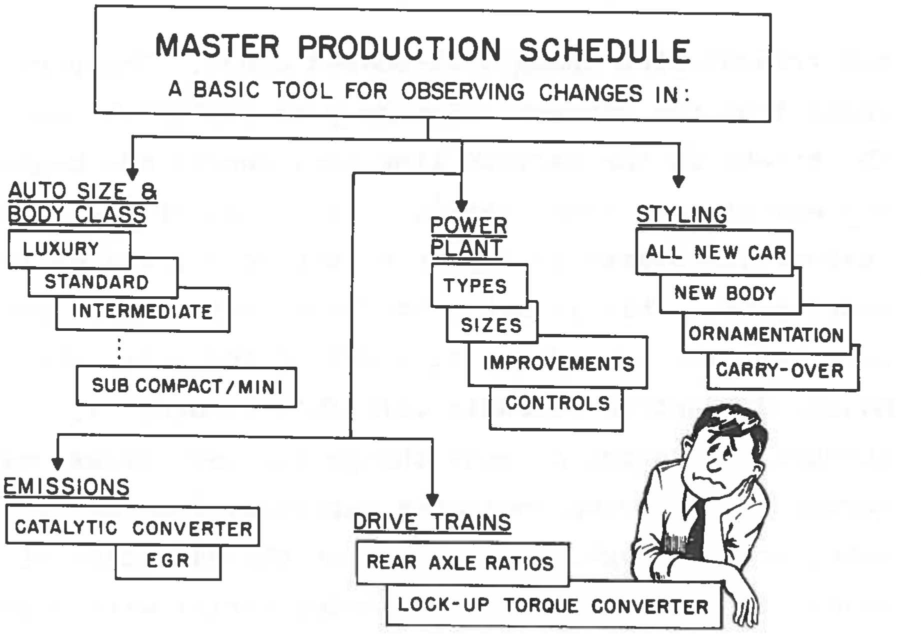


Figure 13. Master Production Schedule

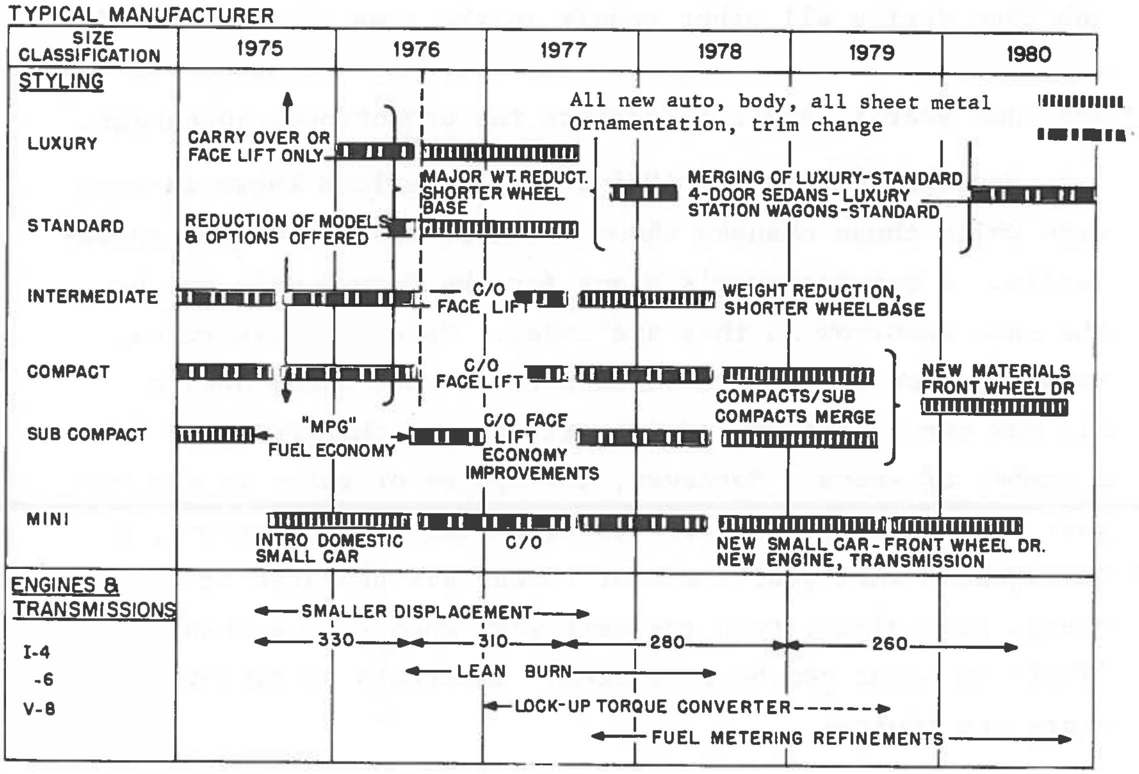


Figure 14. U.S. Passenger Cars — Current and Projected Production Timing

and transmission changes discussed above. The period extends from the current calendar year (1975) through 1980. The breaks in the various time-bars denote the beginning and end of each model year's volume production run which customarily starts in August of the year previous to the model year. This is not a hard and fast rule as new models have been introduced any time during the year, which the Master Production Schedule will duly record. The shading denotes the degree of body change for each class, make and series. No shading indicates carryover from preceding year, or no change. The fact that the same type of body change is often shown for all model series within the same classification is not by accident. The industry typically will introduce a basic body or new auto for a given class, and then derive all other models in the same class from this basic style. The derivatives will often be introduced in the same year in order to capture the promotional advantage.

Styling changes for 1975 and 1976 reflect known information while those changes shown for 1977 and beyond are speculative. A manufacturer's plans for the future will not be the same tomorrow as they are today. Several basic rules, however, prevail: as mentioned before, once a new body or all new car is introduced, it will not be changed again for a number of years. Moreover, new bodies or autos in any one year are limited to one or two size classes. Therefore, if it is known what year the most recent all new auto or body change took place, then the next year when such a change is likely to occur can be predicted. Intervals of five-to-seven years are typical.

All timing projections through 1980 are heavily constrained by the regulatory issues. The increased pressure for fuel economy and the success of fuel efficient foreign imports have forced the industry to concentrate heavily in this area at the expense of the customary emphasis on styling. The emission control requirements alone are in the category of an all new car change when it comes to resource expenditures and investment, and these changes contribute little to shape or style of the car. As Figure 14 indicates, the response towards smaller engines, lighter vehicles and shorter wheel bases shows up in all areas for 1976 on. The reduction of models and options offered for 1976 as well as minimal styling changes, is due in large part to re-direction of resources towards meeting 1979 emission control and fuel economy requirements. However, 1977 and 1978 will most likely see a concentration of weight reduction and shorter wheel bases for the standard and intermediate size vehicles, as manufacturers offer "roominess" on a more economical basis.

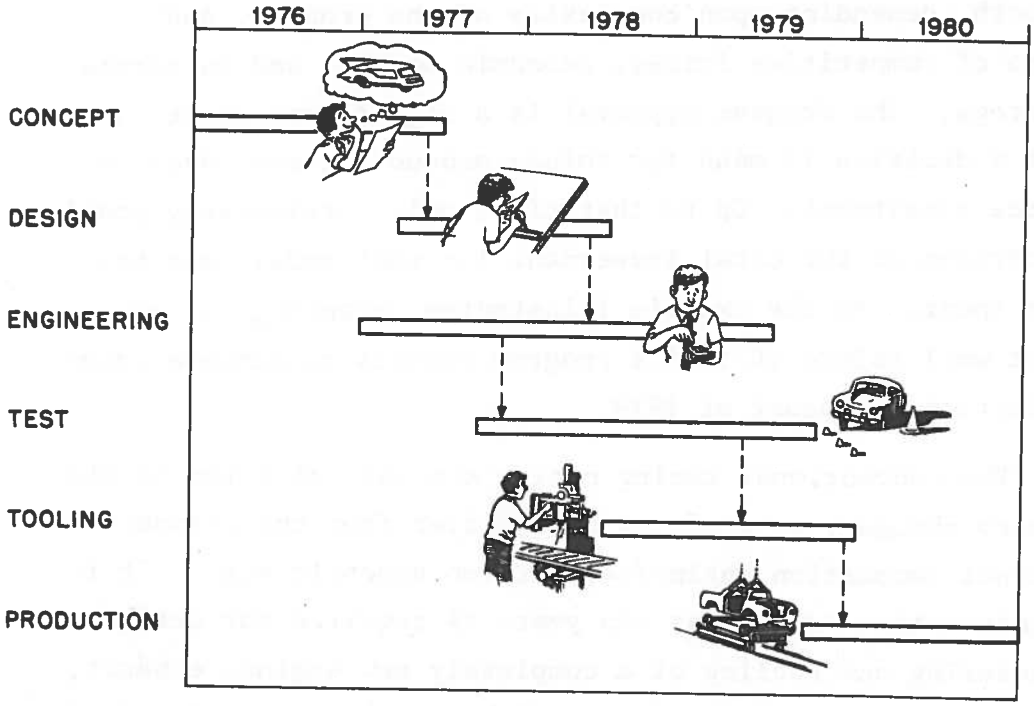
In line with making bigger cars smaller, the big four and two-door sedans in the standard class may very well disappear by 1979 with station wagons only remaining. However, the sedans will likely be available in limited quantities in the luxury class, while the luxury and former standard classes may combine as one class.

The highlight of 1979 model year will probably be the introduction of the domestic small or mini car which emulates the present day foreign import. This vehicle is projected to have a new 4-cylinder tranverse mounted engine, front wheel drive, new materials, better emission control and 40 mpg economy.

## D. Production Timing Phases

The introduction of each new auto, major body and styling change requires a considerable degree of planning and advanced scheduling. It is a complex process with hundreds of inter-locking events. The major phases are illustrated and tabulated in Figure 15 and consist of: concept definition, styling and design, engineering, prototype build and test, tooling and manufacturing and full volume production. This process spans a period anywhere from thirty months to six years depending upon the extent of change, technology required and resources committed. The automotive industry generally uses a 42-month nominal cycle for evolutionary type changes which are applicable to introduction of completely new automobile or major body restyling. This time phasing is a product of 15-to-20 years experience in fine tuning the automotive design and manufacturing process. It is a compromise between resource commitment lead time, and ability to respond to consumer and competitive demands with last minute work-in-process changes. Except for differences among phases, the 42-month timing cycle seems to apply to new engine introductions as well, although engine changes are less frequent (once in ten years) as compared to yearly styling changes.

Figure 16 is an example of the Production Timing Schedule applied to the development of an all new 1979 domestic mini auto and a new 4-cylinder front mounted engine to power it. The time duration and degree of overlapping between each phase should be noted. The major milestones are not precise dates, but often periods extending for weeks, or as much as



| PHASE | DURATION:-MOS. FROM VOLUME PRODUCTION. | ACTIVITY |
|---|---|---|
| CONCEPT - DIRECTION | 27 - 44 | STYLING CONCEPTION<br>ENGINEERING & PRODUCT PLANNING<br>PROJECTED MARKET OPTIONS & STRATEGIES<br>NEW CAR SPECIFICATIONS<br>BROAD DEVELOPMENT OBJECTIVES |
| DESIGN | 12 - 28 | PROGRAM APPROVAL<br>MAJOR RESOURCE COMMITMENT<br>HARD POINTS<br>DETAILED DESIGN & STYLING<br>CLAY MODELS |
| ENGINEERING | 6 - 26 | DETAILED DRAWINGS - PARTS, COMPONENTS, ACCESSORIES, SUB SYSTEM<br>MATERIAL LISTS<br>MANUFACTURING PROCESS<br>TOOLING DESIGN, PATTERNS, DIES |
| PROTOTYPE & TEST | 1 - 23 | ENGINEERING MODELS<br>FULL SCALE APPROVAL<br>TESTING, ENGINEERING & EPA CERTIFICATION |
| TOOLING & FACILITIES | 1 - 16 | SELECTION OF SUPPLIERS<br>PARTS PROCUREMENT<br>INSTALLATION, TEST & CHECK OUT<br>PILOT PRODUCTION RUNS |
| PRODUCTION | JOB # 1+12 | BUILD UP<br>FULL SCALE OPERATION |

Figure 15. Production Timing Phases

a month, depending upon complexity of the program, and tempo of competitive forces, economic market, and corporate strategy. The Program approval is a significant event in that a decision is made for volume production and major resource commitment. Up to that time, only a relatively small proportion of the total investment for that model year has been spent. As the example illustrates, planning has to start well before 1975 if a program expects to achieve volume production by August of 1978.

The conventional timing cycles are not valid for revolutionary changes, or products that differ from the standard internal combustion engine/rear driven domestic auto. It is estimated that as much as six years is required for design, engineering and tooling of a completely new engine, exhaust, drive train combinations which will meet the proposed emission, safety and fuel economy standards. This stretch out is due in part to: absorption of new technology for solving basic regulatory problems (emissions, safety, etc.); development or conversion of manufacturing plants and tooling to build smaller more fuel efficient vehicles; testing and certification of such vehicles; and the orderly phase-in of the new vehicles as the production of conventional autos winds down.

The magnitude of the planning effort can be appreciated from the schedule of Figure 17 by observing what an automotive manufacturer is undertaking in any model year for one size class of vehicle. As an example, in going into the 1976 model year for standard size autos, the manufacturer has: wound-up production for current year (1975); initiated 1976 production on a completely new model, and facelift changes on

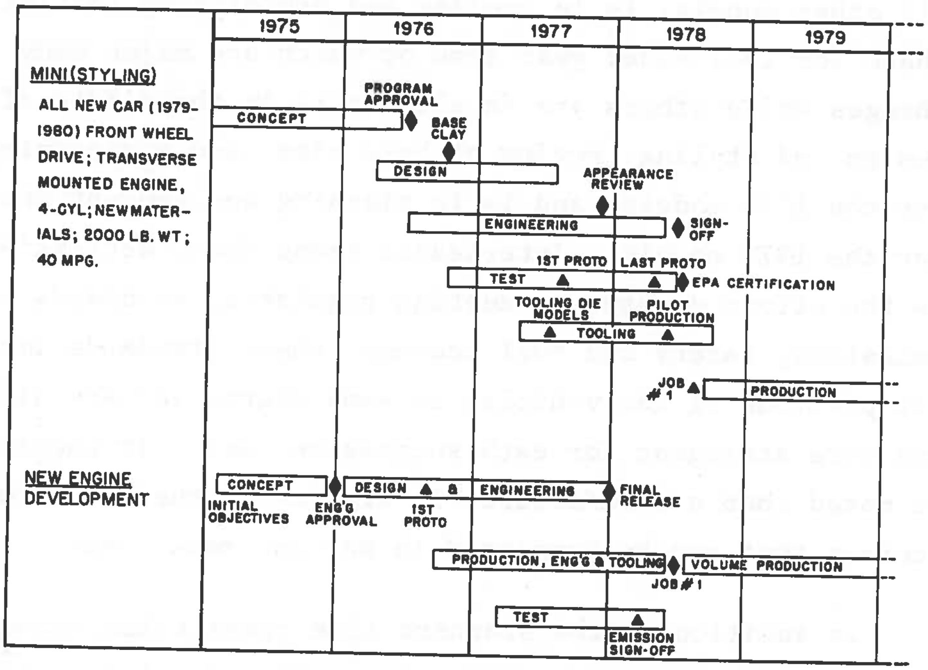


Figure 16. New Vehicle and Engine Timing

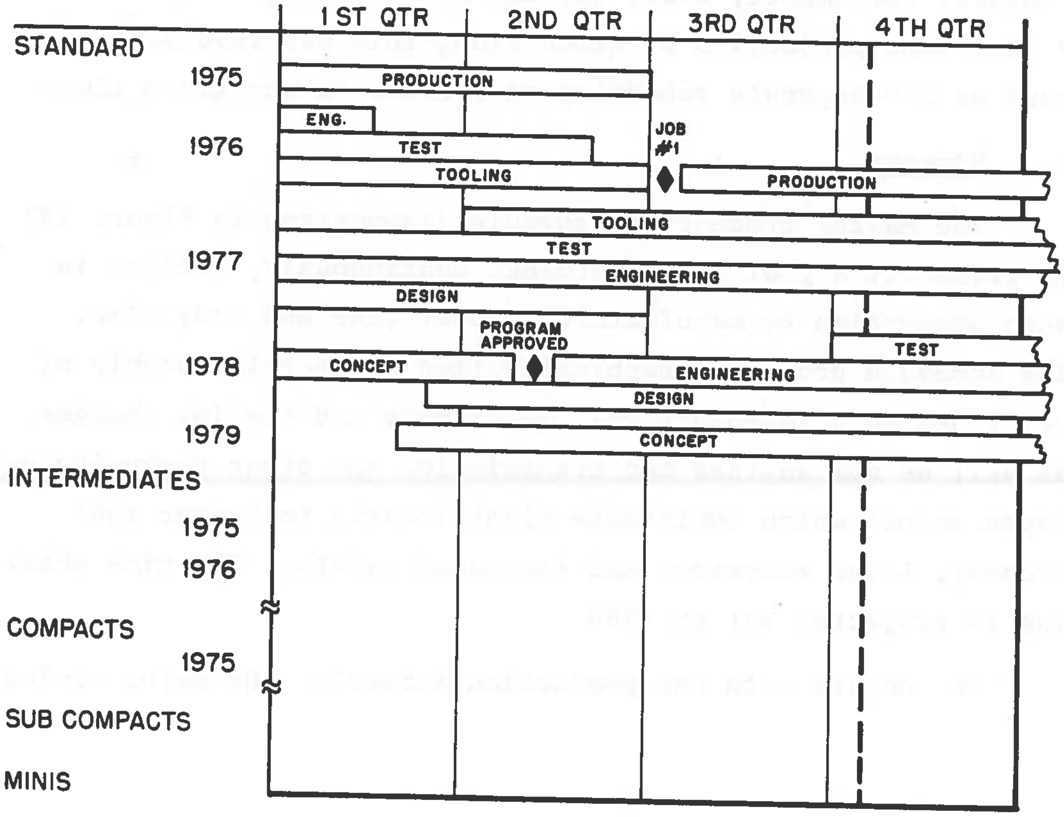


Figure 17. Schedule

all other models; is in tooling and prototyping testing phase for 1977 model year some of which are major body changes while others are facelifts; is in the middle of design and styling, review of base clay, and engineering for the 1978 models; and is in planning and concept phase for the 1979 models. Interleaved among these activities is the effort devoted to meeting regulatory standards for emissions, safety and fuel economy; these standards impact all portions of the vehicles to some degree and are different and more stringent for each successive year. It should also be noted that a manufacturer is limited to the amount of resources that can be committed in any one model year.

In addition to the standard size class illustrated, similar kinds of timing schedules are in play for intermediate, compact, subcompact, etc., for all models being offered. For a five year projection of production, this may involve as many as 250 separate schedules in process at any given time.

## E. Summary

The Master Production Schedule (summarized in Figure 18) is primarily a tool for recording, continuously, changes in auto production by manufacturer, model year and body size. The schedule provides graphically time phase relationship of major new auto introductions, major body and styling changes, as well as new engines and transmission and other technological improvements which contribute significantly to better fuel economy, lower emissions and increased safety. The time phasing is projected out to 1980.

In concert with the production schedule, the major timing phases of the development and manufacturing process are identified and overlayed to obtain guidance and understanding of the lead time associated with the planning and scheduling of new introduction and styling changes for a given model year. The major phases of the manufacturing timing process are: Concept Definition, Styling and Design, Engineering, Prototype Model and Test, Tooling and Facilities, and Full Scale Production.

A TOOL FOR:

- CONTINUOUSLY RECORDING
  - PRODUCTION BY MODEL YEAR & BODY SIZE
  - BODY & ENGINE CHANGES
  - NEW AUTO, ENGINE & TRANSMISSION INTRODUCTIONS
- UNDERSTANDING THE DEVELOPMENT & MANUFACTURING PROCESS

| | |
|---|---|
| CONCEPT | PROTOTYPE - TEST |
| DESIGN | TOOLING & FACILITIES |
| ENGINEERING | FULL SCALE PRODUCTION |

- EVALUATING THRU 1980
  - LEAD TIME
  - CHANGE INTERVALS
  - MILESTONES & DECISION POINTS

Figure 18. Summary—Master Production Schedule

# DEVELOPING A DATA BASE OF THE U.S. AUTOMOBILE SERVICE AND REPAIR INDUSTRY

Principal Investigator - Donald A. Hurter
Arthur D. Little, Inc.

## ABSTRACT

The purpose of this contract is to develop the maintenance portion of the life cycle cost data for automobile and light trucks to be used in conjunction with the automotive manufacturing data base. All repair and service data is to be gathered from existing publications, surveys and manufacturer's literature.

The following tasks are included as part of the data base development:

- Determine the vehicle manufacturer's scheduled and unscheduled maintenance and repairs required for the life cycle of each selected model and year of the representative 210 different vehicles from 1970-1975. Provide the materials and labor costs for each maintenance task required.
- Determine the facilities, tooling, equipment, capital investment, special skills, labor and materials required to perform the maintenance of a vehicle. Determine which kind of service facility, service station, independent garage, specialty shop or franchised dealer would typically perform the maintenance for the representative vehicles as a function of vehicle age and mileage. Determine the cost differential for performing the repairs and service at the four various kinds of maintenance facilities.
- Analyze the collected data to determine the relationships between maintenance cost versus the following parameters: manufacturer, body size, model year, initial purchase price, engine size, and type of emission control equipment.
- Analyze the collected data to determine trends in industry pricing policies and price differences between proprietary and non-proprietary parts.
- Project future changes in maintenance costs and in maintenance facilities resulting from possible technological changes in vehicles related to improved fuel economy or improved emission control on manufactured vehicles for the period 1975-1980.

## PURPOSE OF THE PROJECT IS TO DETERMINE:

- Maintenance Requirements for 1970-1975 Model Vehicles
- Facilities and Investment for Performing Maintenance
- Relationship Between Maintenance Costs and Various Vehicle Parameters.
- Pricing Policy for Maintenance Cost
- Future Trends in Maintenance Cost 1975-1980, 1980-1985

## PARTICIPANTS IN THE PROJECT

Arthur D. Little – Principal Investigators

Chilton Company – Data Source for Maintenance Cost, Required Facilities and Pricing Analysis

Rath & Strong – Co-Ordination with Manufacturing Data Base and Procedures

### TABLE OF 1970-1975 MOTOR VEHICLES BEING EXAMINED IN THIS PROJECT

(Approximately 40 Individual Models for Each Year)

| | MANUFACTURER | | | | |
|---|---|---|---|---|---|
| BODY SIZE | FORD | GENERAL MOTORS | CHRYSLER | AMC | FOREIGN |
| LUXURY | 1 | 3 | – | – | – |
| STANDARD | 1 | 1 | 2 | 1 | – |
| INTERMEDIATE | 1 | 2 | 1 | 1 | – |
| COMPACT | 2 | 2 | 2 | 2 | – |
| SUBCOMPACT | 2 | 3 | 1 | 1 | 4 |
| MINI | – | – | – | – | 1 |
| TRUCK 0-6000 LBS | 1 | 1 | – | – | – |
| TRUCK 6000-10,000 LBS | 1 | 1 | – | – | – |

## MOTOR VEHICLE CLASSIFICATION BY BODY SIZE

### Standard

Chevrolet (Impala, Bel Air)
Chrysler (Newport)
Ford (Galaxie, Custom)
Plymouth (Fury)
American Motors Company (Ambassador)

### Intermediate

AMC (Matador)
Chevrolet (Chevelle)
Ford (Torino)
Plymouth (Satellite)
Pontiac (Grand Prix)

### Compact

AMC (Hornet)
Chevrolet (Nova)
Dodge (Dart)
Ford (Mustang, Maverick)
Plymouth (Valiant)
Chevrolet (Camaro)
AMC (Javelin)

### Subcompact

Ford (Pinto)
Chevrolet (Vega)
AMC (Gremlin)
Volkswagen (Rabbit)
Toyota
Datsun
Ford (Capri)
Buick (Opel)
Dodge (Colt)
Mazda
Olds (Starfire)

### Luxury

Cadillac (Eldorado)
Lincoln (Continental)
Buick (Electra 225)
Cadillac de Ville

### Mini

Honda Civic

### Truck 0-6000 Pounds

Chevrolet C-10
Ford F-100

### Truck 6000-10,000 Pounds

Chevrolet C-20
Ford F-250

## MAINTENANCE REQUIREMENTS FOR 1970–1975 MODELS

- Determine the Retail Cost for Vehicle Manufacturers' Scheduled Maintenance (SM) and Cost for Unscheduled Maintenance and Repair (USM) for Life Cycle of Vehicles

RESULTS OF THIS TASK WILL BE:

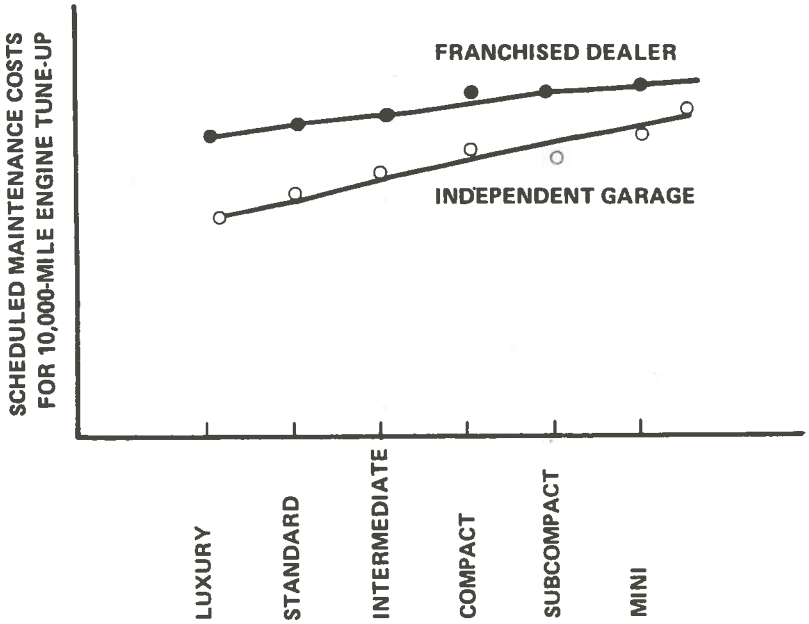
- Definition of the Life Cycle of an Automobile in Miles and Years
- SM and USM Functions and Retail Cost of Material and Labor for Each Specified Vehicle as Performed by the
  - Dealer
  - Specialty Shop
  - General Repair Shop
  - Service Station

## FACILITIES AND INVESTMENT FOR PERFORMING MAINTENANCE

OBJECT

- Determine the Facilities, Tooling Equipment, Capital Investment, Special Skills, Labor and Materials to Perform Maintenance for Entire Fleet of Vehicles.
- Classify and Compare by:
  - Kind of Facility
  - General Condition-Mileage, Age
  - 1st or Subsequent Owner

## HYPOTHETICAL EXAMPLE OF COMPARISON OF MAINTENANCE COSTS FOR ENGINE TUNE-UP BY DIFFERENT SERVICE FACILITIES

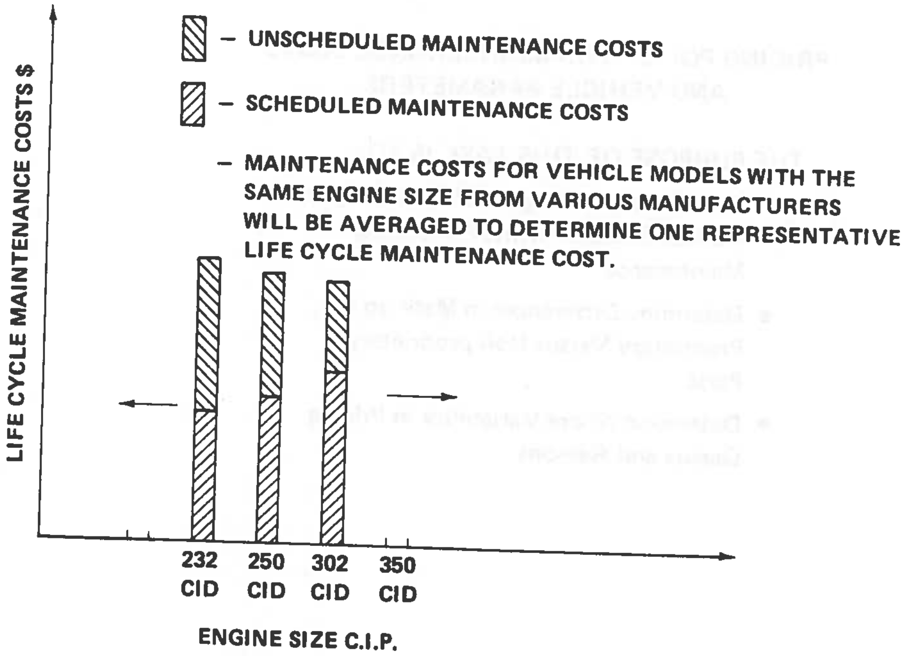


## RELATIONSHIP BETWEEN MAINTENANCE COST AND VEHICLE PARAMETERS

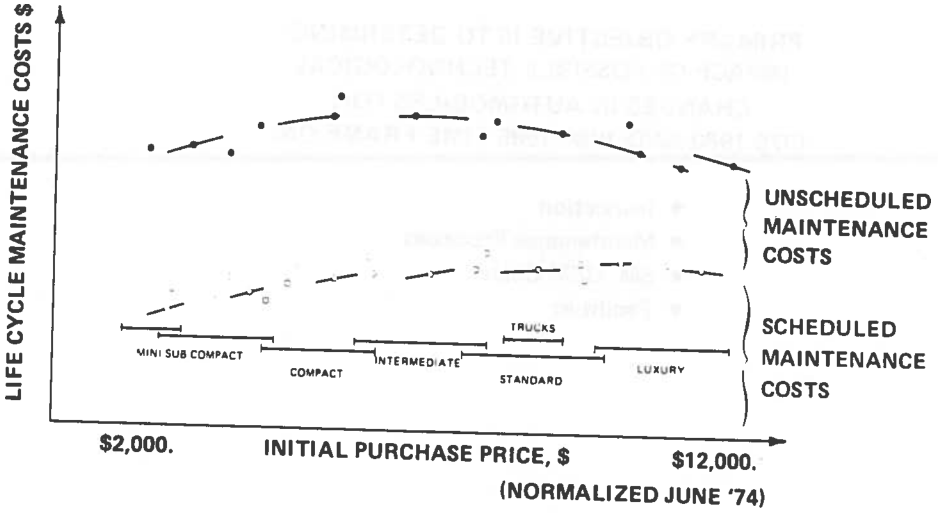
Develop Relationship Between Costs for SM and USM Versus:

- Manufacturer
- Body Size
- Model Year
- Initial Sticker Price
- Engine Size
- Type of Emission Control Equipment

HYPOTHETICAL EXAMPLE OF LIFE CYCLE MAINTENANCE COSTS VS. ENGINE SIZE



HYPOTHETICAL EXAMPLE OF LIFE CYCLE MAINTENANCE COSTS VS. PURCHASE PRICE



## PRICING POLICY FOR MAINTENANCE COSTS AND VEHICLE PARAMETERS

THE PURPOSE OF THIS TASK IS TO:

- Describe the Pricing Policies Used by the Various Establishments Performing Maintenance
- Determine Differences in Mark-up for Proprietary Versus Non-proprietary Parts
- Determine Where Variability in Pricing Occurs and Reasons

## FUTURE TRENDS IN MAINTENANCE COSTS 1975-1980 AND 1980-1985

PRIMARY OBJECTIVE IS TO DETERMINE:
IMPACE OF POSSIBLE TECHNOLOGICAL
CHANGES IN AUTOMOBILES FOR
1975-1980 AND 1980-1985 TIME FRAME ON:

- Inspection
- Maintenance Processes
- SM, USM Costs
- Facilities

## EXAMPLES OF TECHNOLOGICAL CHANGES ARE:

### 1975-1980

- Lighter Weight Bodies
- Material Substitution-Aluminum, Plastics
- Increased Use of Radial Tires
- Engine Modifications Involving Catalytic Converters, HEI Ignition
- Electronic: Spark, Fuel and Air Control

### 1980-1985

- Lightweight Diesel
- Four Speed Automatic Transmission With Lock-up Torque Converter
- Possible Introduction of Alternate Engines

## GENERAL OBSERVATIONS TO DATE

- Variation Between Manufacturers' Specified Scheduled Maintenance
- Preventative Scheduled Maintenance Technological Versus Policy Reasons
- Consumers' Acceptance of Scheduled Maintenance
- Cost Effectiveness of Performing Scheduled Maintenance
- Realism of Specified Scheduled Maintenance, e.g., Emission Controls
- Impact of Technological Improvements on Where Maintenance is Performed
- U.S. Versus Foreign Car Specified Maintenance
- Variation in Data Collected by Fleets, Government Agencies and Others
- Maintenance as Performed by First Owner and Subsequent Owners
- Decrease in Service Station Maintenance Facilities
- Characteristics of Pricing Policy
- Condition of Repair for Cars in States Having Mandatory Versus Non-Mandatory Inspection

# MANUFACTURING TECHNOLOGY ASSESSMENT

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## ABSTRACT

The Manufacturing Technology Assessment Program effort is subdivided into eight (8) tasks which are relevant to the production of energy efficient automobiles. Specifically, these tasks address the areas of:

- Automatic transmissions with lockups
- Lightweight body materials
- Mass production tooling
- Effect of part tolerances on fuel economy
- Fuel injection systems
- Catalytic converters
- Lightweight diesel engines
- Input to the report of the Automotive Manufacturing and Maintenance Panel of the Task Force on Motor Vehicle Goals beyond 1980.

The review will present the methodology used in each of the tasks to accomplish the program objectives and also preliminary conclusions in areas where they have been granted.

## 1. INTRODUCTION

The Manufacturing Technology Assessment Program effort is subdivided into eight tasks which are relevant to the production of energy efficient automobiles.

Specifically, these tasks address the areas of automatic transmissions with lockups, lightweight body materials, fuel injection systems, catalytic converters, lightweight diesel engines, mass production tooling, and the effect of part tolerances on fuel economy.

## 2. OBJECTIVES

The primary objective of this program is to assess the manufacturability, costs, and approximate lead times to implement the above energy related components. The mass production tooling task is to assess the current and future technology of transfer lines for engines, transmissions, engine accessories, etc. Data from this task will also be used to support scenarios for implementing the above energy related components.

The objective of the part tolerances study is to determine the areas of the automobile where fuel economy is most sensitive to tolerances and to assess the magnitude of the effects in the most sensitive areas.

## 3. METHODOLOGY

The initial effort in each task is a literature search to generate a library of background material. The literature includes trade publications, technical papers (particularly by the Society of Automotive Engineers) and technical data published by manufacturers. Pioneer personnel have attended relevant technical meetings in the Detroit area, such as the recent seminar on light weight materials conducted by the American Society of Body Engineers. In addition, Pioneer is interviewing knowledgeable personnel from automotive supplier companies to obtain their comments on present state-of-the-art and future trends.

Production costs of each of the energy related components are being generated by similar methods. For example, Pioneer has been directed to "perform an assessment of the manufacturability of the four-speed transmission with lockup in high; the four-speed transmission with lockup in 2nd, 3rd, and high; and the wide-range, three-speed transmission with lockup." A lockup is a device, such as a clutch, which diverts the power flow through the transmission past the torque converter, thus eliminating the slip and resultant power loss associated with the torque converter.

For this study, Pioneer procured a Borg-Warner Model 45 automatic transmission (Fig. 1). This unit is manufactured in England and is used on a variety of subcompact automobiles. The transmission was disassembled following procedures set forth in the manufacturer's Service Manual (Fig. 2). This allowed us to observe the manufacturing operations employed and the assembly procedures which are somewhat different from U.S. production procedures. We also noted the basic differences between this transmission and the type that would be used on an American vehicle.

For instance, the torque converter housing and transmission housing are separate units bolted together (Fig. 3). Borg-Warner uses this method because this transmission must be fitted to a variety of engines built by many manufacturers. U.S. production vehicles, because of much higher volume and less variety, employ an integral torque converter and transmission housing.

The next step was to design a lockup. There were two used in U.S. passenger cars about two decades ago. The system presently used in the Allison truck transmission was adapted for two basic reasons:

(1) It is representative of current technology.

(2) It operates through several transmission gear ratios while the transmission is shifting.

Manufacturing assessment of the lockup system includes an analysis of parts added and modification of existing parts to accommodate the lockup. No attempt is made to determine the cost of the basic transmission. We are interested in the cost and lead time required to incorporate the lockup over and above that of the standard transmission.

Standard cost analysis procedures are employed to establish the part and assembly costs. The build-up of costs are generated by listing each step in the process, calculating material costs, and part production rates per hour to allocate labor costs and machine occupancy time. Burden rates are established for the type of machines used. An allowance for material scrappage is added to the above costs to provide the total part cost.

As the cost penalty for this lockup is being determined, data for an American built unit will be generated, allowing for the differences in design, manufacturing and production quantities. This data will be combined with input from the mass production tooling task to construct scenarios as required in the Work Statement.

A similar approach is being used for the lightweight diesel engine task. A Perkins six cylinder diesel engine was selected for analysis (Fig. 4). This engine is being considered by several American manufacturers as an optional light truck production engine. Its application and displacement of 247 cubic inches (4.05 liters) are typical of six cylinder passenger car engines. It represents the latest in lightweight, thin wall rib reinforced casting technology.

Pioneer is investigating the conversion of gasoline engine manufacturing facilities to diesel engines. Some required changes are obvious. For example, the carburetion and ignition systems of the gasoline engine will be replaced by the diesel injection system, sometimes called the 'plumber's nightmare.' Required changes in the head, pistons, connecting rods and crank are obvious and frequently discussed in the literature. However, more subtle differences

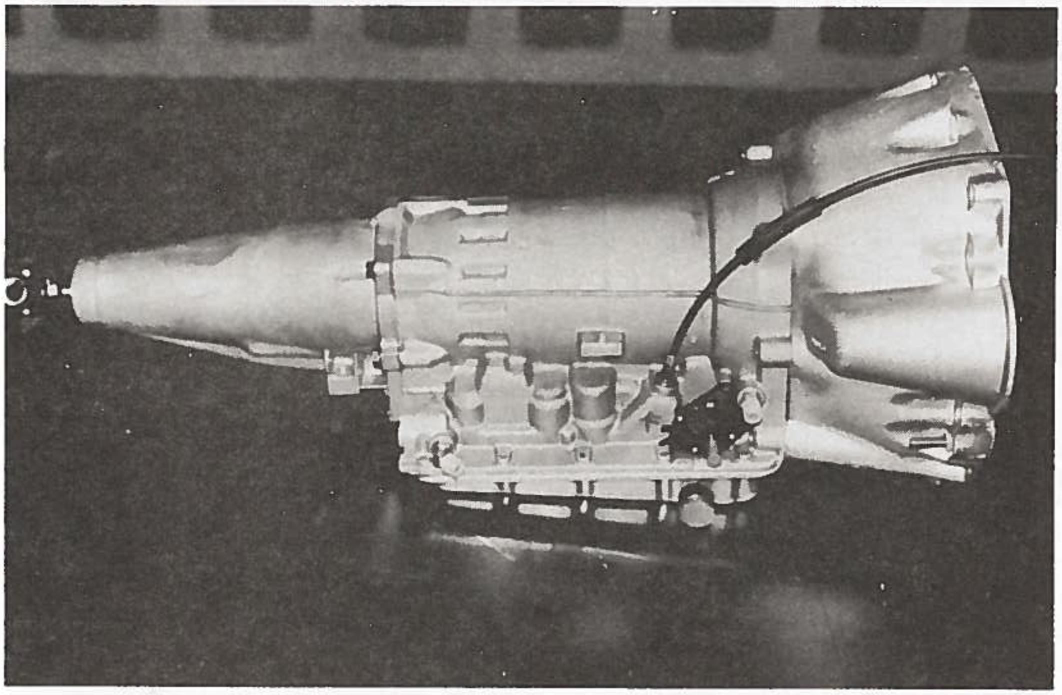

Figure 1. Borg-Warner Model XT Automatic Transmission

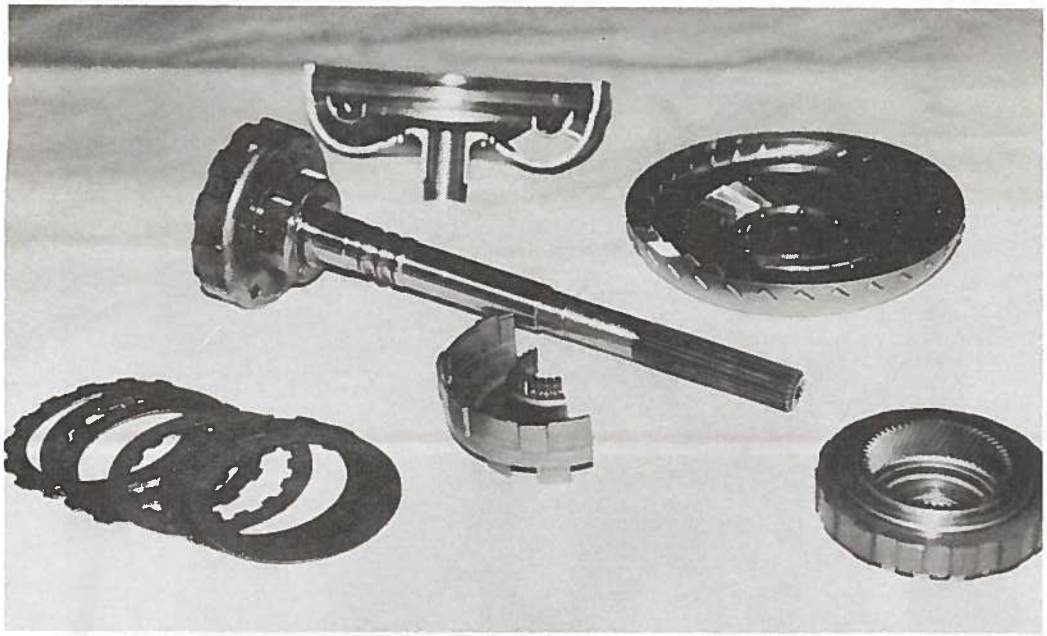

Figure 2. Disassembled Transmission

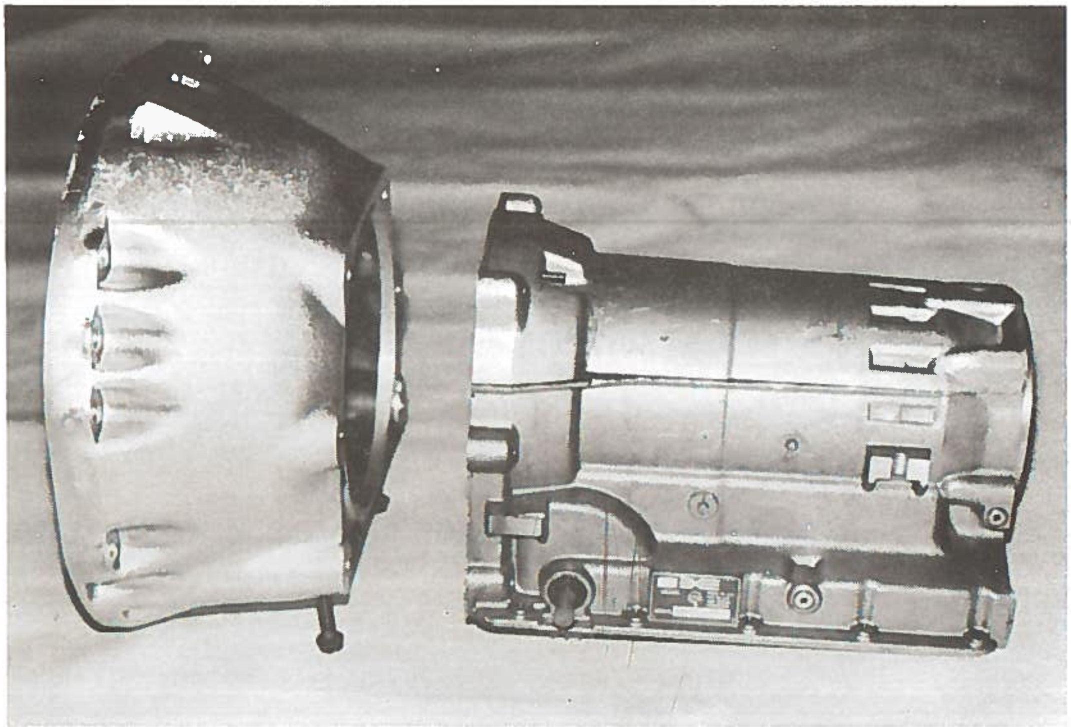

Figure 3. Transmission Housing and Torque Converter Housing

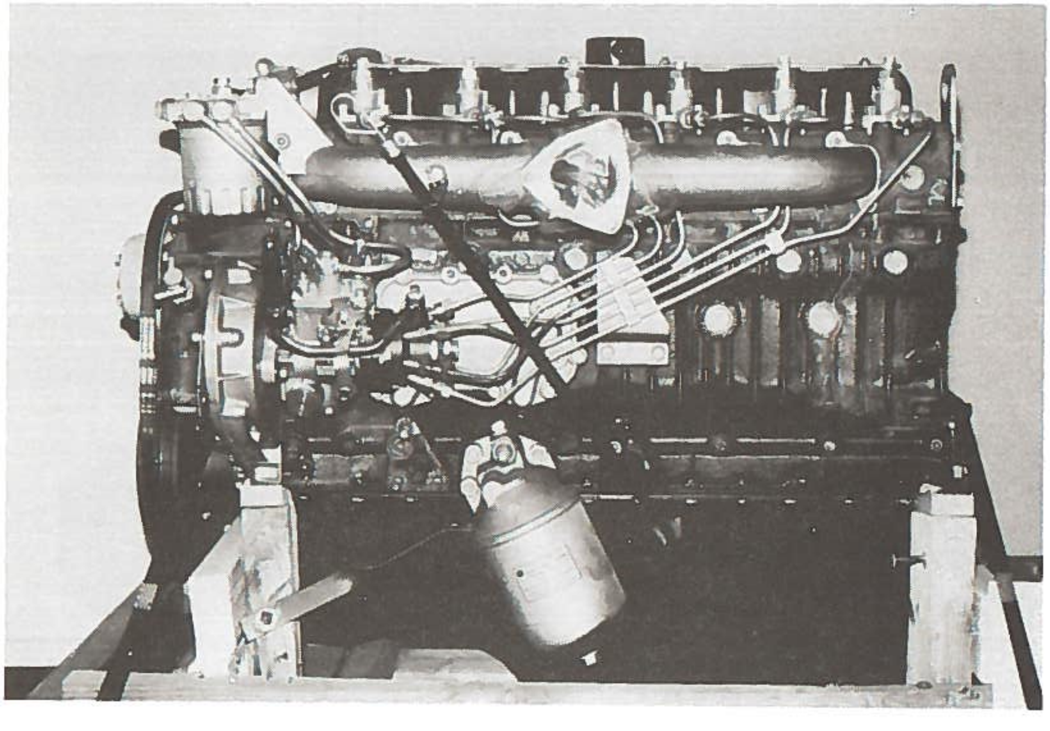

Figure 4. Perkins Six-Cylinder Engine

between diesel and gasoline engines exist accounting for significant differences in design and tooling. For instance, the high pressures and large fluctuations in diesel engine torque require increased stiffness and damping capacity in the block and crank. Thermal stability criteria dictate changes in engine coolant flow and capacity which in turn affect engine block configuration. Frankly, it is alarming to see scenarios for converting passenger car gasoline engines to diesel engines of equal displacement and nearly equal performance. Conversion on this basis has not yet been done successfully and is therefore not current state-of-the art. This study should give us the capacity to determine just what type of conversion can be made, including such factors as cost, time required for the change, and the expected level of performance. At this point in the study, it appears that the capacity of the transfer machine industry will be a major constraint on lead time. If, for example, all gasoline engine lines were to be converted to diesel, it would take 10 to 12 years to manufacture and install the maching transfer lines with current tooling industry capacity.

The tasks on catalytic converters and fuel injection will be accomplished in a similar manner.

The lightweight body component study will be based on substituting materials for Pinto body components. A Pinto car has been disassembled (Fig. 5) and part and assembly costs have been generated. Lightweight materials will be substituted, where applicable, and costs and tooling requirements generated.

The part tolerance study began with a literature search which yielded very little qualitative and no quantitative data. It is common knowledge that increased clearances in certain key areas reduce friction, but there seems to be no

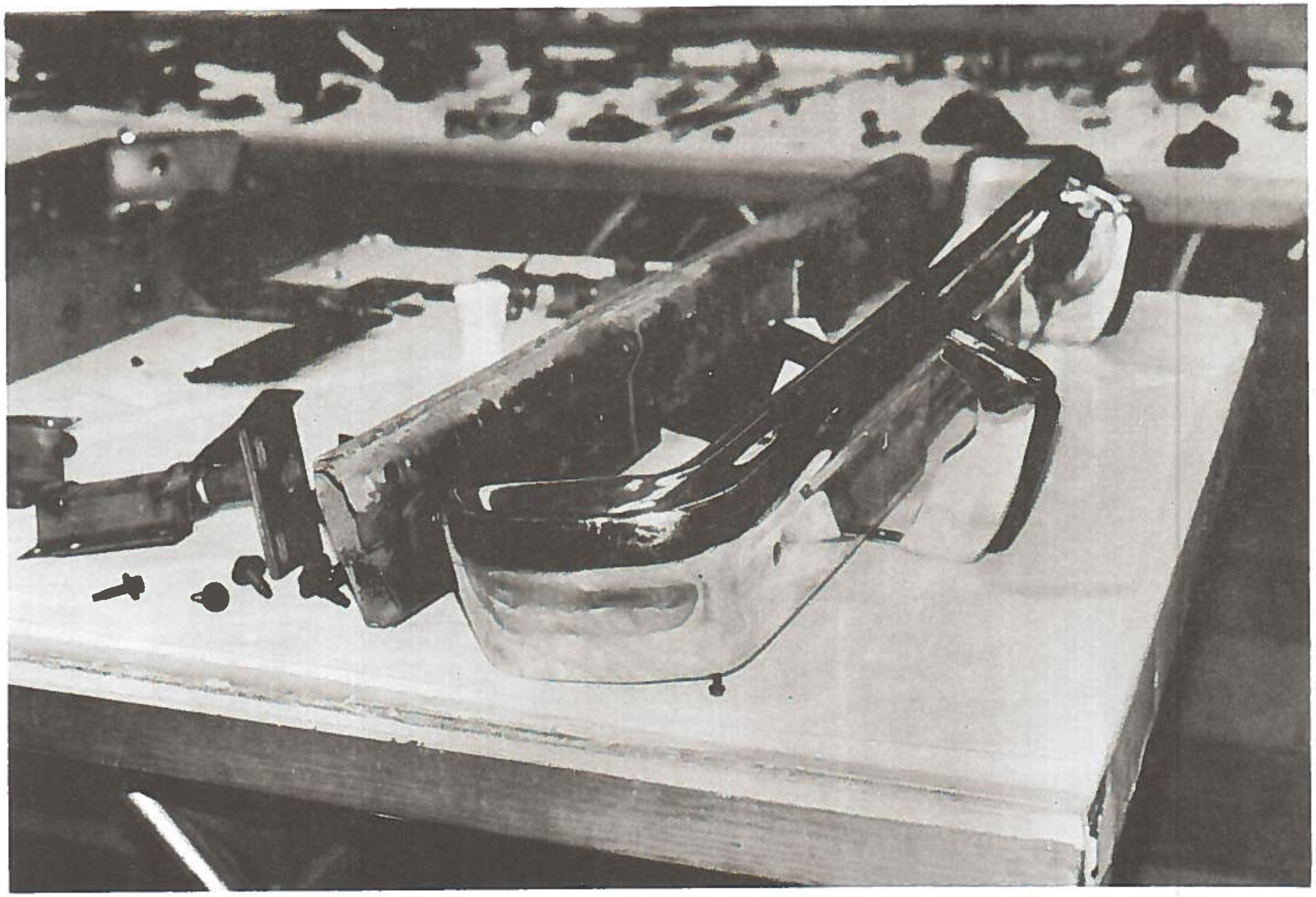

Figure 5. Parts From Disassembled Pinto

documented information on how much reduction is gained for a given amount of change. It is common practice to prepare cars specially for drag strip and economy competition with extra clearances in critical areas. However, the cars also exhibit excessive noise, wear, oil consumption and exhaust emissions.

Recent advances in manufacturing technology have allowed automobile manufacturers to reduce tolerances. As a result, there has been considerable tightening up, but the objectives have been reduced noise, wear and emissions rather than fuel consumption. For example, carburetor tolerances have been tightened to the limit of current technology and stacked to favor emissions control. Despite such favoritism, economy has suffered little, if any. One carburetor manufacturer reports that a test conducted three years ago, when tolerances were looser, pitted 20 carburetors specially built to nominal dimensions against twenty selected at random. There was no measurable difference in fuel economy.

Computerized controls on the automobile tend to make manufacturing tolerances less critical even while constraining the performance of a system to narrower limits. These controls typically respond to feedback from sensors which detect system output. Adjustments are made to achieve correct output and manufacturing tolerances are effectively over ridden.

Pioneer is investigating other vehicle dimensions and the effect of these variations on fuel economy. The first step was to determine the areas of the automobile which consume the most horsepower and where variations in tolerances have the greatest effect. This is accomplished by evaluating efficiency data.

Efficiency data over the vehicle operating range are available on components such as torque converters, transmissions, axles, etc. In addition, the effect of vehicle dimensions on power requirements is also known. In some cases, such as vehicle weight, the variation within manufacturing limits is small but consistent.

In the case of vehicle attack angle, the variation within manufacturing limits varies between limits with no really significant deviation (about 2-1/2%).

In the case of vehicle frontal area, the steepness of the lines indicate that some significant variation could be expected (Fig. 6). The variation shown, plus or minus one quarter inch all around, is hypothetical and is used here only to demonstrate the methodology. Actual values for variation will be used in the analysis. The mathematical model for calculating horsepower is shown in the upper right-hand corner. It contains terms and factors for wind force, tire drag and chassis friction.

The final step in the analysis is to translate frontal area into fuel economy (Fig. 7). The mathematical model employed in this step combines required horsepower with other vehicle factors, such as brake specific fuel consumption, wheel revolutions per mile, axle ratio, etc.

The mass production tooling task requires a state-of-the-art study. A literature search and interviews with knowledgeable personnel are being employed taking input from machine tool manufacturers as well as automobile manufacturers. The study will include the history of machining transfer lines; gross and net production rates, cost of designing, building and installing; operation cost; lead time requirements; plant and site requirements; flexibility; the capacity of the industry to produce machinery;

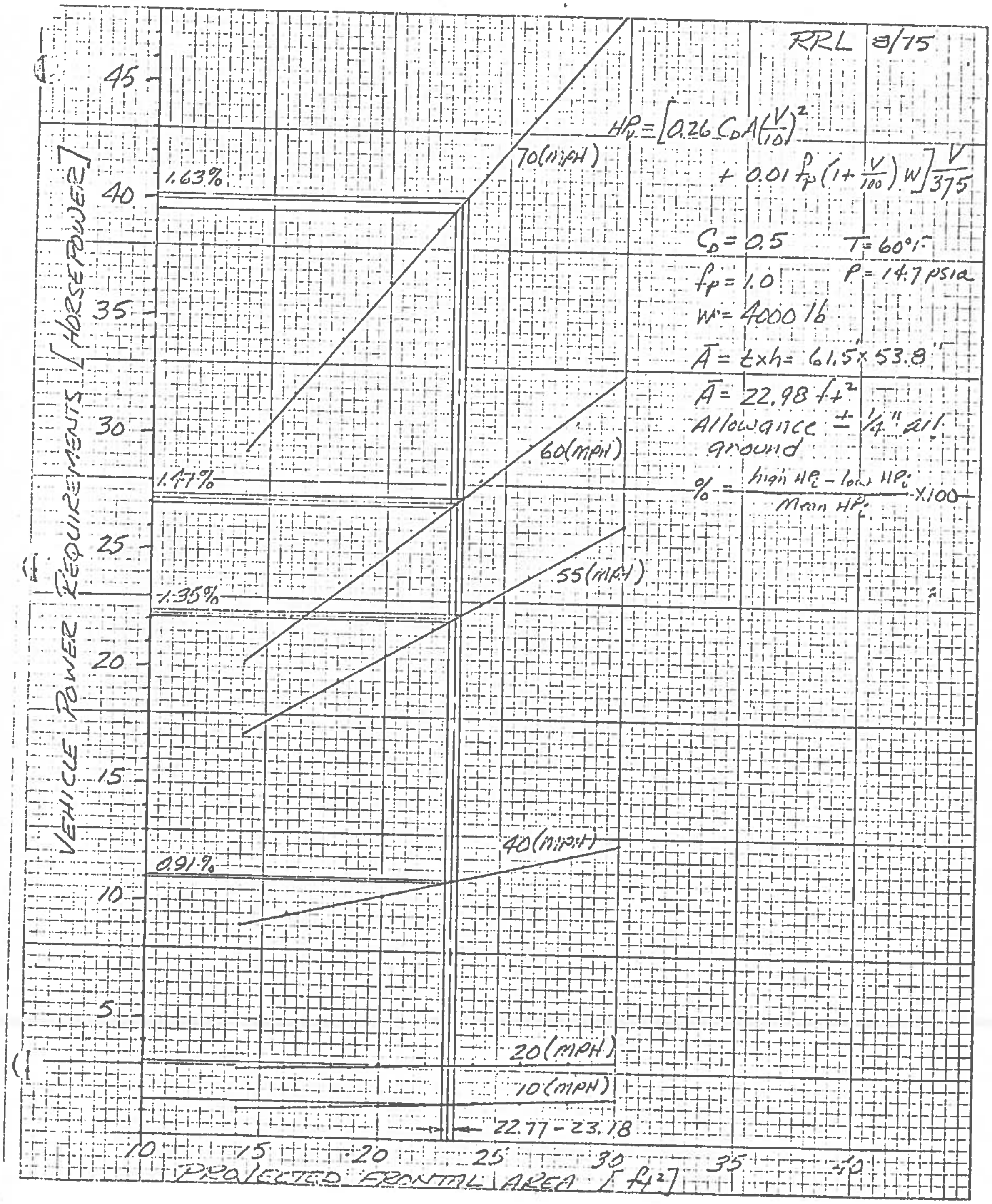

Figure 6. Vehicle Power Replacements Vs. Frontal Area

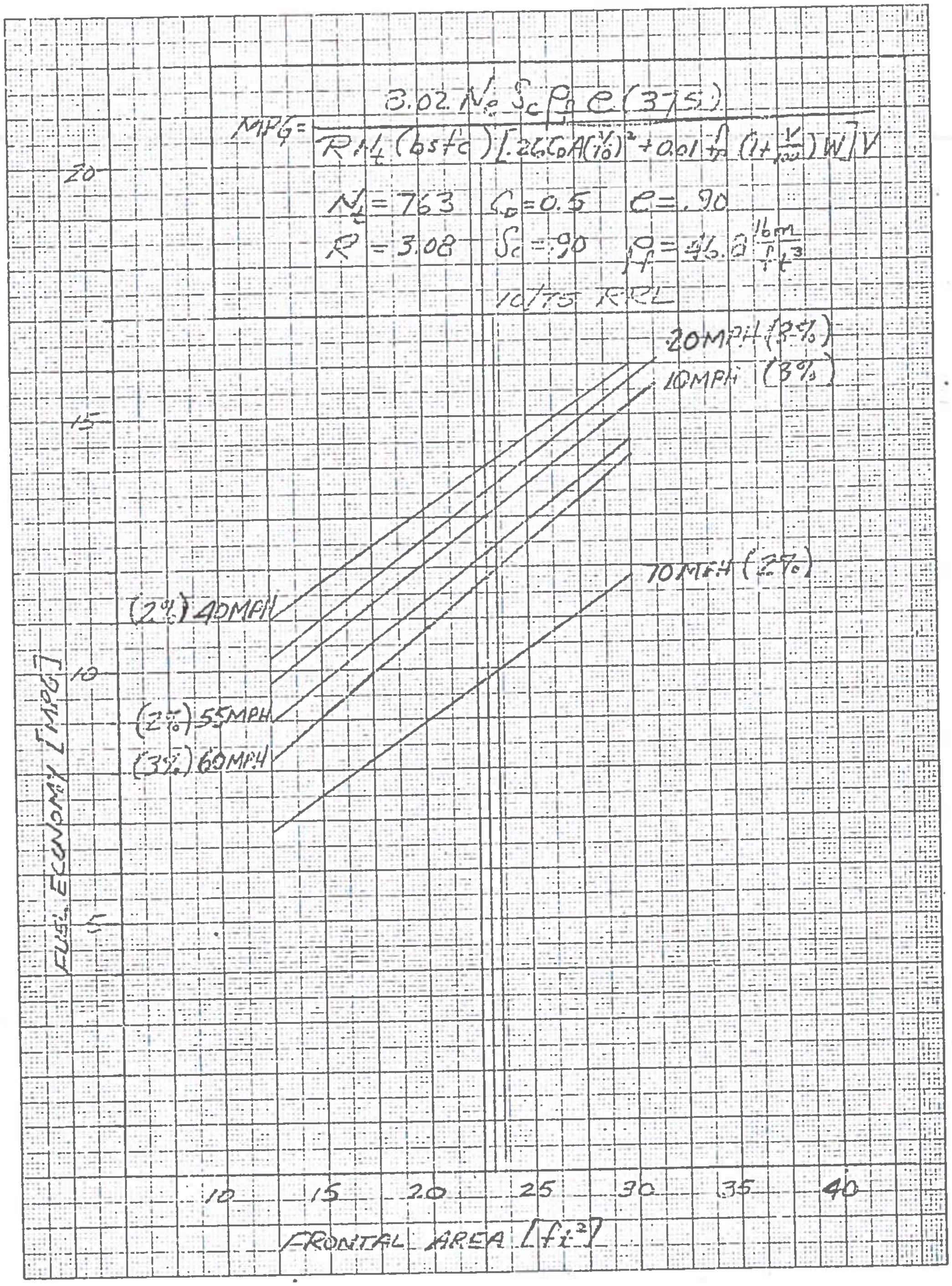

Figure 7. Fuel Economy Vs. Frontal Area

capital intensity; manpower intensity; and computerized controls. Output from this task will be used in the other tasks to generate the required scenarios.

Typical of the data we are generating, Table 1 shows the cost of tooling an engine. These figures are based upon the cost in 1975 dollars of building an all new line. The cost of rebuilding and converting an existing line would be less, the actual amount depending upon the extent of the changes and the condition of the machinery.

TABLE 1. ENGINE TRANSFER LINE TOOLING COST

| Component | Cost in $1,000,000 for:<br>4 Cylinder | <br>8 Cylinder |
|---|---|---|
| Block | 12 | 18 |
| Head OHC/cam-in-block | 6.6/5 | 12 |
| Crank | 10 | 10 |
| Piston | 4.5 | 6 |
| Cam | 6 | 6 |
| Manifold, intake | 2.5 | 3.5 |
| Manifold, exhaust | 3 | 6 |
| Water pump | 1 | 1 |
| Oil pump | 2 | 2 |
| Bearing cap | 2 | 3 |
| Connecting rod and cap | 4 | 6 |
| Distributor gear | 2 | 2 |
| Total at vendor's floor | 54 | 75.5 |
| + 30% transportation, installation and tryout | 16 | 22.5 |
| TOTAL INSTALLED.................. | 70 | 98 |
| GRAND TOTAL including vendor's tooling cost | 115-125 | 150 |

# AUTOMOBILE SCRAPPAGE AND RECYCLING INDUSTRY

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## ABSTRACT

After an automobile has lost its utility as a mode of transportation it is deregistered and enters the scrap market. At present approximately 10 million passenger automobiles and light trucks are deregistered annually in the United States. Each vehicle has a potential scrap materials value of about $100 apiece in the 1975 market. The flow of junk automobiles and recovered materials through the established commercial recovery cycle is presented with emphasis on the recovery of ferrous scrap from stripped automobile hulks. The impact of new scrap reclamation technology and the increased demand for ferrous scrap is discussed. An empirical demand curve correlating the number of auto hulks processed with the price of ferrous scrap has been developed.

It is concluded that the increased value of ferrous scrap has provided the financial incentive necessary to create a strong demand for auto hulks. This has apparently reversed the problem of an increased accumulation of abandoned, derelict cars, which existed in the 1960's.

## INTRODUCTION

After a motor vehicle has lost its utility as a mode of transportation, it is deregistered and enters the scrap market. There are a number of major industries in the United States that perform a useful economic function by salvaging equipment and materials from scrapped automobiles. These are the auto wrecking industry, the scrap processing industry and the secondary smelting industry. Because of the collection, processing and purification steps that occur after an automobile is scrapped, the utility of the materials used to make the automobile transcends the useful life of the automobile, as shown in Figure 1. This figure outlines the cycle associated with the utilization of automotive materials. It shows that from cradle to grave, all phases of the life of an automobile are interrelated.

The automobile recycling process starts when the last owner decides that a particular vehicle is no longer economical to operate, that it cannot be re-sold as a mode of transportation, and the auto is released to an auto wrecker. As shown in Table 1, the potential scrap value of the materials in a junked automobile is approximately \$100/car in the present market for metal scrap. This assumes total separation and recovery of the metals as distinct commercial grades of scrap. Since approximately ten million cars and light trucks (herein grouped as automobiles) are deregistered annually, the recovery of metals from scrapped automobiles is a $1 billion/year activity that handles approximately 15 million tons of metal per year.

On the average, an automobile will be about ten years old when it is deregistered, i.e., retired and withdrawn from the active inventory. Newer automobiles are deregistered, principally, as a consequence of automobile accidents. Older cars are deregistered principally because of wear. Most deregistered autos enter the system of collection and recycling through legitimate commercial transactions. A certain portion, however, are abandoned by their owners and become a problem for local authorities. These vehicles are impounded under law by the local authorities so that they do not remain an eyesore and a public nuisance. In the cities, the abandoned vehicles are nearly all collected promptly by municipal authorities or their contractors and, thus, enter the scrap cycle. In rural areas, without state or county statutes, this mechanism does not exist. Control of the accumulation of abandoned vehicles is dependent on volunteer action or on roaming collectors.

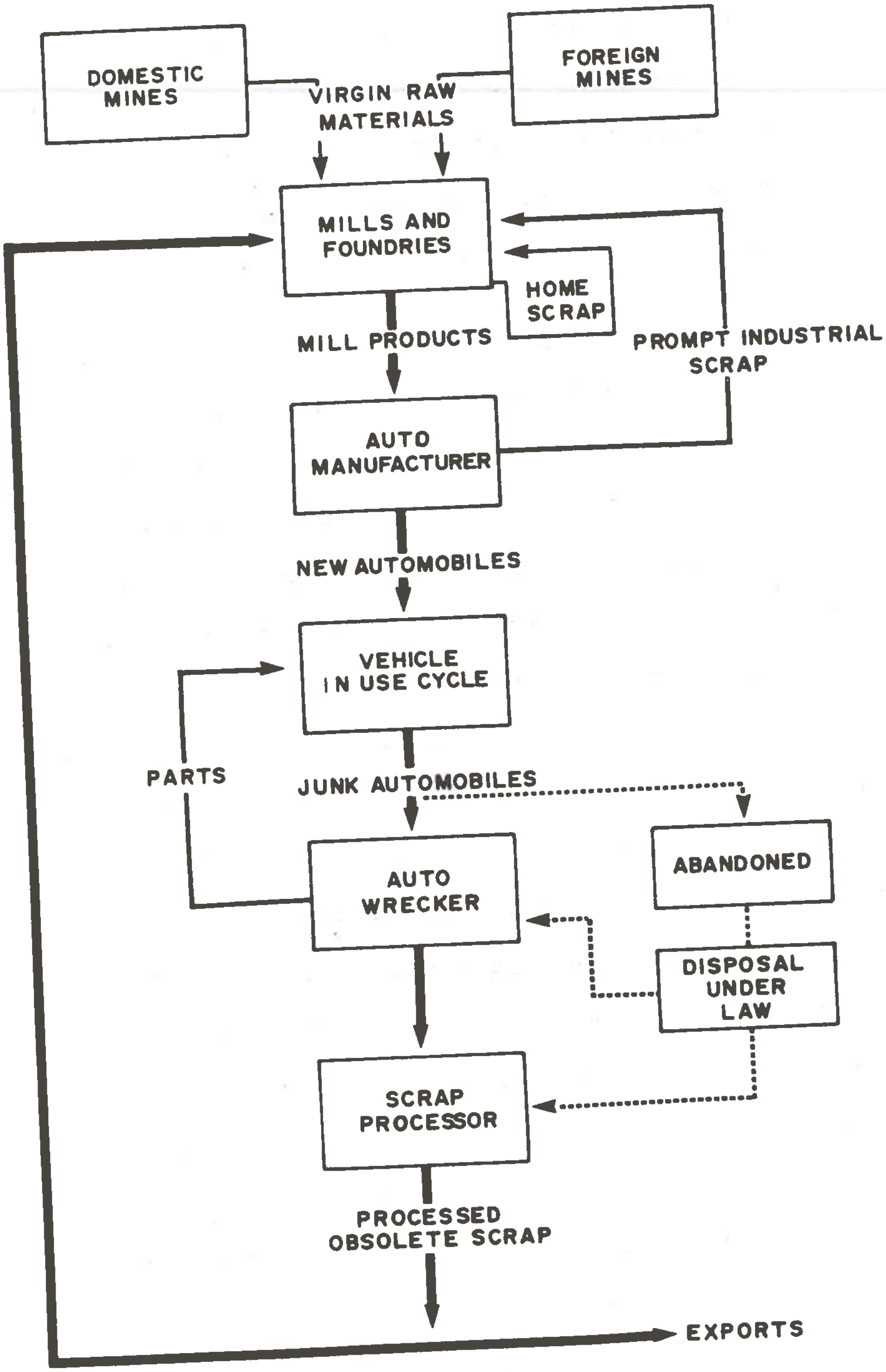

Figure 1. Automobile Material Cycle

TABLE 1. SCRAP VALUE OF JUNK AUTOMOBILE (1 JULY 1975)

| MATERIAL | CONTENT (LBS.) | MATERIALS VALUE (PER CAR) |
|---|---|---|
| FERROUS METALS | 2700 | $77 |
| NON-FERROUS METALS | 200 | 26 |
| NON-METALS | 600 | - |
| TOTAL | 3500 | $103 |

The auto wrecking industry, which has wide geographical coverage, acts as a collection point for obsolete vehicles. The auto wrecker obtains obsolete vehicles from the public and uses them as sources of parts.

The parts stripped by a wrecker have a number of markets. Some parts are sold directly to consumers for further transportation uses, some parts are sold to reconditioners for ultimate transportation re-use, and others are sold to scrap metal dealers for the value of contained materials. These are items which are easily removed and have a relatively high value, such as radiators and batteries.

After the vehicle is stripped of marketable parts, the residual is a vehicle hulk that requires disposal. The outlet for these vehicle hulks is the scrap processor who buys them for further processing into ferrous metal scrap. These hulks are usually flattened prior to shipment, often with a mobile flattener, which permits more hulks to be transported on a truck, thus greatly increasing the distance a hulk can be economically transported. This is of special importance to wreckers in remote parts of the country.

## FERROUS SCRAP PROCESSING

The principal product obtained from a junk automobile is ferrous metal scrap, with a typical hulk yielding slightly less than a ton of steel. The scrap processor transforms the auto hulk into one of three specific grades of scrap that can be sold to steel mills either in the United States or abroad. Depending on the type of equipment available, a hulk can be transformed into (1) shredded scrap, (2) a #2 bundle, or (3) auto slab. Shredded scrap commands a much higher price than the other two grades because it is fairly free of contamination by dirt and nonferrous metals.

Number 2 bundles consist of old black and galvanized steel sheet scrap, compressed to charging box size and weighing not less than 75 pounds per cubic foot. They may not contain tin-coated, lead-coated, or vitreous enameled material, but may contain auto body and fender stock, burned or hand stripped. A #2 bundle is essentially an auto hulk, free of combustibles and the drive train, that is compressed hydraulically into a smaller package that is easier to handle. Based on an equipment survey conducted by ISIS (Institute of Scrap Iron and Steel) in 1970, there are approximately 1,500 hydraulic presses in the United States. Depending on its size, a baler will cost between $200,000 and $500,000. Typically, a baler could process between four hulks per hour and up to 20 hulks per hour which corresponds to an annual steel output of from 10,000 tons per year to 50,000 tons per year.

Number two (#2) bundles have limited acceptability to iron and steel makers due to their high level of impurities in the form of nonferrous metals and dirt. The most serious contaminant is copper whose presence affects the drawing quality and surface of the finished steel.

Automotive slab is a related grade of scrap. An auto hulk is first compressed into a log-shaped bundle, then fed into a hydraulic guillotine shear which slices the scrap into slabs of design size. Depending on its size, the shear represents an investment of between $200,000 and $700,000. In 1970, according to the ISIS survey, there were approximately 500 such shears installed in the United States. The quality of scrap produced is similar to that of #2 bundles.

Shredded or fragmentized scrap steel is the product of a shredding system that consists, basically, of a 1,000-4,000 horsepower impact crusher or hammermill to reduce the auto into smaller fragments, nominally, less than eight inches in maximum dimension, and one or more magnetic drums which separate the liberated iron and steel from the non-magnetic metals and nonmetallic material. The purified iron and steel is the principal product. The non-magnetic portion is treated in an auxillary air classifier to remove the dirt and fluff from denser portions of the non-magnetic stream which contains the nonferrous metals. This secondary product is sold to specialized processors who separate the principal nonferrous metals contained. The shredder produces a higher quality of scrap than #2 bundles while accepting a more contaminated hulk as a feed. Combustible materials do not have to be removed by hand stripping or incineration for the hulk to be an acceptable feed for a shredder.

Shredders have had a major impact on the industry since their introduction in the early 60's. According to recent estimates, there are presently about 200 shredders in operation in the United States. A shredder, depending on its size and costing up to $4 million, can process approximately 25,000 to 250,000 automobiles a year.

The capacity of the scrap processors to handle ferrous scrap greatly exceeds the amount of auto scrap steel produced. The amount of such scrap processed is not limited by equipment capability, but by market demands. The total capacity of the balers, shearers, and shredders in this country is on the order of 40-50 million tons of steel scrap per year.

## PRODUCTION OF FERROUS SCRAP FROM AUTO HULKS

The amount of ferrous scrap produced from auto hulks can be estimated by using a procedure developed by Booz Allen Applied Research Inc. as part of a prior study for EPA (Reference 1). This method is based on the statistical information of domestic consumption and exports of various grades of ferrous scrap published by the U.S. Bureau of Mines. (USBM) (Reference 2) The Booz Allen method assumes that 58% of the weight of #2 bundles and 85% of the weight of shredded steel, as reported by USBM are auto derived. The method further assumes a constant limited amount of auto slab production (800,000 tons/yr).

The estimated annual recovery of steel scrap from junked automobiles for the period 1965 to 1975 is presented in Figure 2. The 1975 data are based on statistics through 30 June 1975. As can be seen in this figure, steel scrap production was fairly constant from 1965 to 1971, and then increased rapidly in the period of time 1971 to 1975. Steel scrap production increased from a base line value of about 5 million tons a year and rose to a value approaching 9 million tons per year. The rise in steel scrap production from automobile hulks reflects principally the increase in shredded steel production. Between 1965 and 1975, shredded steel production increased from approximately less than a million tons per year to nearly five million tons per year at the present time. During this same period of time, there was not a marked change in No.2 bundle production which hovered at approximately 3 million tons per year. No. 2 bundle production declined from 1965 to 1971 and then increased again in the past few years.

The increasing number of auto hulks being processed annually, reflects an increasing demand for obsolete ferrous scrap. The relative importance of auto hulks in the ferrous scrap market is shown graphically in Figure 3. As can be seen in this Figure, ferrous scrap from auto hulks represents about 12 to 14% of total purchased scrap (including exports), and about 22 to 28% of obsolete scrap processed in this country.

## MARKET FOR FERROUS AUTO SCRAP

The consumption of auto hulks by scrap processors is mainly a function of the demand for purchased ferrous scrap by steel mills and foundries. Five factors affect this demand:

A. The market for finished iron and steel products.

B. Technology of steel manufacturing and of foundry practice, i.e., type of furnace used.

C. Availability and/or cost of competitive material (pig iron, direct reduced ores, etc.) relative to scrap.

D. Specifications of the steel to be produced.

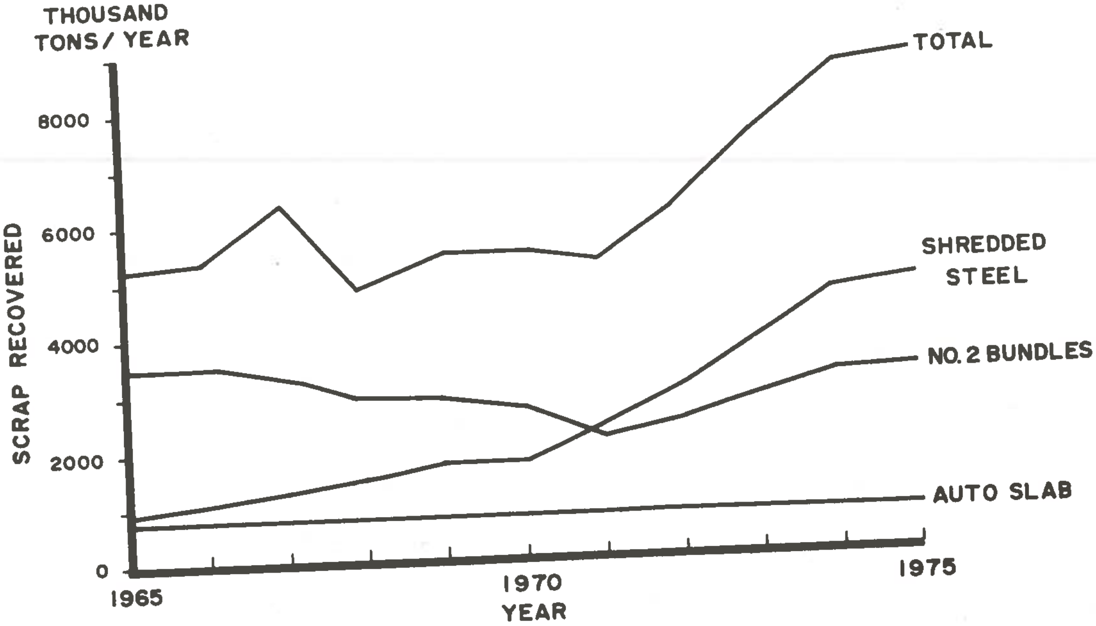

Figure 2. Annual Recovery of Steel Scrap From Junked Automobile Hulks

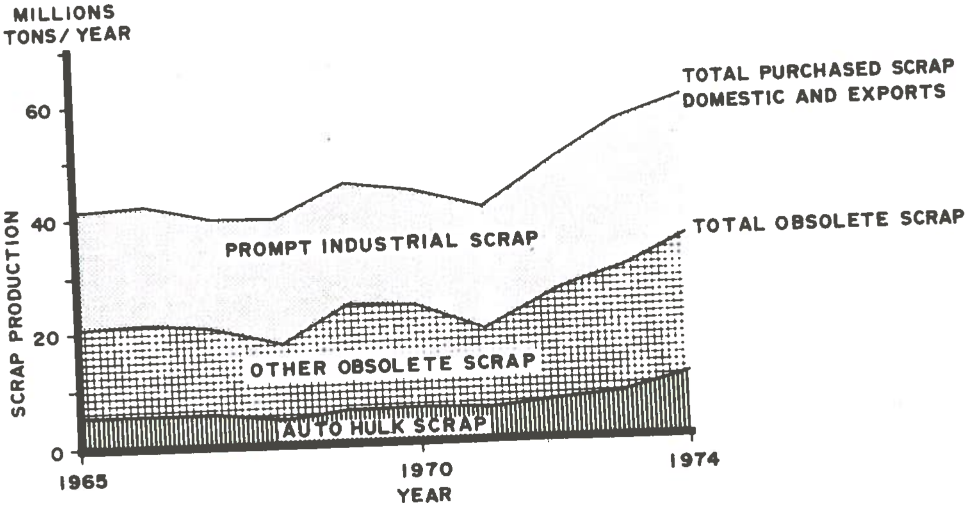

Figure 3. Impact of Ferrous Scrap From Auto Hulks

### E. Quality of the scrap produced.

There has been a sharp increase in the price of ferrous scrap since 1971. Composite scrap prices for No. 1 heavy melting steel scrap and No. 2 bundles, as published in Iron Age, are presented for each of the years 1965 to 1975, in Figure 4. Between 1971 and 1974, there was approximately a threefold increase in the price of No. 1 heavy melting steel scrap and approximately twofold increase in the price of No. 2 bundles.

The price of No. 2 bundles is representative of the price of No. 2 bundle steel obtained from junked automobiles and of auto slab steel obtained from the same source. The No. 1 heavy melting steel scrap price is considered representative of the price of shredded scrap. Actually, this grade of scrap sells at a 10 to 20% premium over No. 1 heavy melting steel scrap. However, published records of the price of fragmentized scrap have not been developed to the same extent as the price of No. 1 heavy melting steel scrap. Therefore, for the purposes of this study, it will be assumed that fragmentized scrap sells at the same price as No. 1 heavy melting steel scrap.

The principal competitor of scrap in the manufacture of ferrous products is pig iron which is normally obtained from virgin materials (iron ore, coal, lime). Scrap is utilized to the extent that it is cheaper to use than pig iron. The cost of making a ferrous unit will also vary with the type of furnace involved and the details of a particular steel making operation. The main reason why the price of scrap has increased so dramatically in the past few years has been a dramatic increase in the price of pig iron. While most of the pig iron produced is intended for captive use, and therefore no price is available, there is sufficient merchant pig iron sold for it to be quoted in Iron Age Magazine. The annual average composite pig iron price for the period 1965 to 1974 is also presented in Figure 4. As can be seen the price of pig iron has increased in the past few years from a base price of $63.11 per long ton in 1965 to an average price of $124.38 per long ton in 1974.

The similarities in the historical behavior of the price of steel scrap between 1965 and 1975, and the amount of steel scrap obtained from automobile hulks during the same period, indicates that the two are correlated. It should be possible, because of the wide ranges in the prices of scrap and the production figures, to develop a supply curve for automobile derived steel scrap production as a function of the price of scrap. The price used to characterize automobile derived steel scrap is defined by the following equation:

$X = YS + Z(1-S)$

Where:

$X$ = the weighed average price of steel scrap,

$Y$ = the annual composite price for No. 1 heavy melting steel scrap

$Z$ = the annual composite price for No. 2 bundle scrap

$S$ = the fraction of shredded scrap in steel recovered from auto hulks.

This weighed average price is used to take into account the changes in percentage of shredded steel scrap over the years and the variation in the ratio of the prices of No. 2 bundle and No. 1 heavy melting steel scrap.

There is a high degree of correlation ($r = 0.89$) for the data presented in Figure 5. The line of regression can be expressed by the following least mean square, straight line fit of the data:

$Y = 65.93\ X + 3741$

Where:

$Y$ = the nominal production of steel scrap from automobile hulks in $10^3$ short tons per year and:

$X$ = the weighed average price of steel scrap, \$1 long ton.

The standard error of estimate for this data is equal to $S_Y = 459\ 10^3$ tons per year. The 95 percent confidence

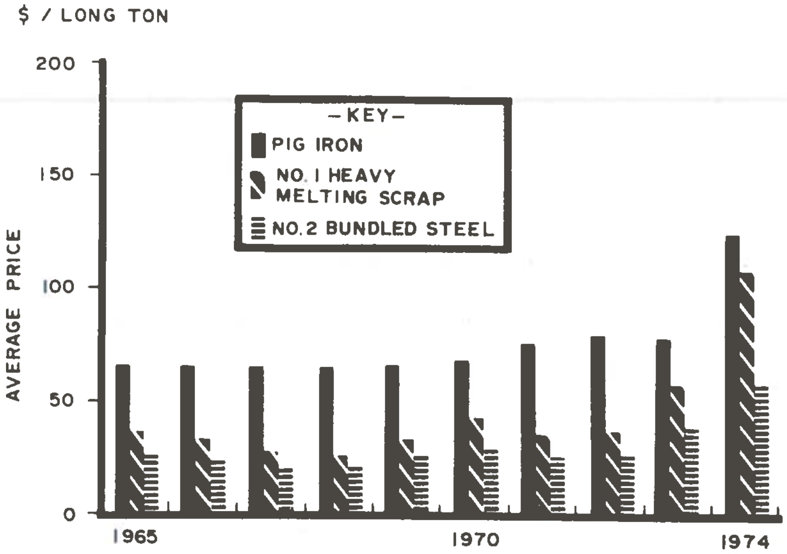

Figure 4. Average Price of Pig Iron Vs. Ferrous Scrap, 1965-1974

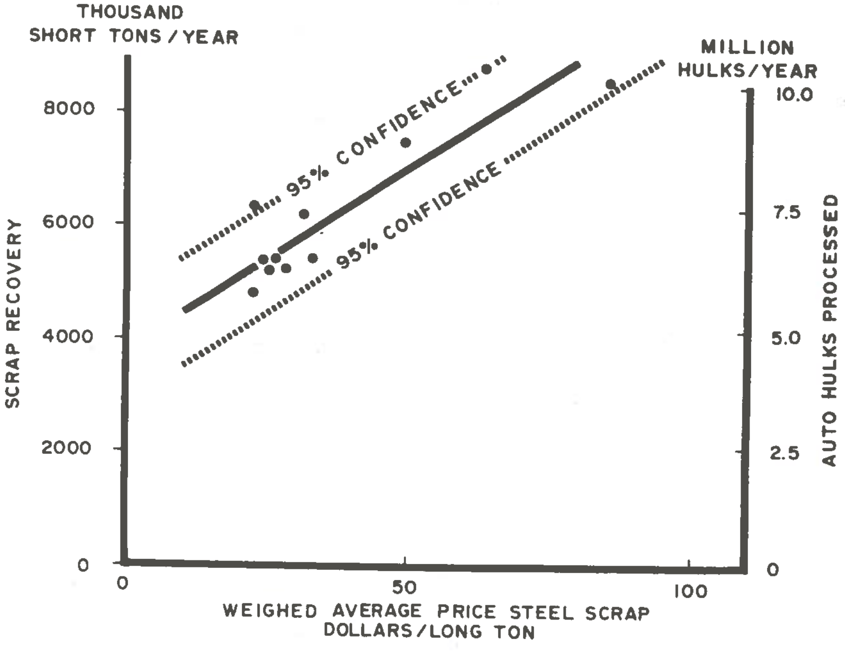

Figure 5. Supply Curve for Steel Scrap From Automobile Hulks, 1965-1975

limits are two parallel lines separated from the regression line by a distance equal to 2 $S_Y$ or approximately 908 X $10^3$ tons per year. Historically, when the price of steel scrap is approximately 25 dollars a ton, between 5 million and 5.5 million tons of steel scrap are recovered from automobile hulks. Increasing the price of scrap to $50 a ton will result in an increased steel scrap production of approximately 7 million tons per year. A further increase to $80 per ton will result in the production of 9 million tons per year of auto hulk derived steel scrap.

Since an average hulk yields approximately 1700 pounds of steel scrap (Reference 3), Figure 5 is also a demand curve for auto hulks, correlating the number of hulks processed as a function of scrap price. This chart can also be used to predict the number of auto hulks that will be processed in a given steel scrap market. When the price of steel scrap is $25/ton, approximately 6.3 million cars can be expected to be processed. When the price of scrap rises to $80/ton, approximately 10.6 million hulks can be expected to be processed. The number of hulks processed at the lower price level, is less than the number of cars deregistered leading to an accumulation of hulks. At the second price level the expected number of hulks processed is slightly higher than the number deregistered in the U.S.

In the 1960's, when ferrous scrap was selling for about $25/ton, there was a problem with the accumulation of unprocessed hulks in the country. In a 1970 report (Reference 4), it was estimated that there were over 15 million unprocessed hulks in the country. While most of these were in the yards of auto wreckers, there were about four million abandoned hulks in the U.S. Auto wreckers did not search or seek to collect these abandoned cars because it would cost them more than the $10 or so they could expect to receive from a scrap processor for a delivered hulk.

This situation no longer exists. With rising scrap prices, the prices paid for a hulk have risen from $25 to upwards of $40 in the past few years. This has proven to be sufficient incentive for wreckers to actively solicit hulks and to move the hulks already in their yards to scrap processing facilities.

At a June 1975 meeting of the U.S. Department of Commerce Industry Advisory Committee on Metal Scrap Problems, representatives of the Automobile Wrecking Industry indicated that there were very few hulks presently in auto wrecker yards and that most had been sold in the past few years.

## Conclusions

There is an established and functioning commercial system to handle the scrappage of deregistered automobiles. The flow of junk automobiles is not limited by processing capacity, but rather by the market price of ferrous scrap, the principal product from junk cars. In the past few years, the price of ferrous scrap has more than doubled. This has proven to be an effective incentive for the movement of hulks from the public sector to the auto wrecking and scrap processing industries. They are now actively soliciting hulks in order to produce scrap. This appears to have corrected the national problem of auto hulk accumulation which was of concern in the past decade.

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# MODELING VEHICLE MILES OF TRAVEL: THE STATE OF THE ART

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## ABSTRACT

A summary of findings and conclusions towards assessing the state of the art of modeling Vehicle Miles of Travel (VMT) by passenger automobiles is presented. The increasingly important role of VMT as a parameter for national policy-making is considered, followed by a description and analysis of the principal lines of historical research on VMT. From this assessment the structural requirements for an improved VMT model are described, and the major problems now hindering its development are listed.

## INTRODUCTION

Vehicle miles of travel (VMT) by passenger automobiles is an important determinant of gasoline consumption, ambient air quality, highway safety, and economic well-being in the United States. Changing patterns and trends in VMT have profound implications for energy conservation, environmental quality, and economic stability. Forecasts of likely future levels of VMT have become a central input to transportation policy analysis.

At present, however, VMT forecasts are made with simplistic analytic techniques. Most projections rely on historical trend analysis, an approach that can be useful when the data exhibit a stable pattern over time and only short-term extrapolation is required. Unfortunately, the historically stable growth in VMT was eroded by the Arab oil embargo and associated increases in gasoline price. Further, effective policy analysis requires extended forecasts to evaluate long-range energy conservation and environmental protection strategies. While a few simple models of VMT, embodying some behavioral economic relationships, have been developed in the past several years, they contain theoretical and empirical shortcomings that render their forecasts little better than standard trend extrapolation.

Because of these limitations in the state of the art, together with the central significance of auto travel for public planning, the Automotive Energy Efficiency Program (AEEP) of the U.S. Department of Transportation, has made development of an improved VMT model one of its objectives. The work reported here, sponsored by the AEEP, was an effort to assess the state of the art of VMT forecasting and map out strategies for extending it. The capabilities of currently available forecasting techniques were compared with the requirements and goals of an improved model of auto travel. Existing sources of information on VMT were reviewed and additional data requirements identified. Based on these assessments, a research plan for developing improved VMT forecasting techniques was outlined.

This paper summarizes findings and conclusions. The following section outlines the increasingly important role of VMT as a parameter for national policy-making. The principal lines of historical research on VMT are then described and strengths and weaknesses of each identified. Drawing on this assessment, the structural requirements for an improved model of VMT are laid out and the major problems now hindering its development are listed.

## VMT AND PUBLIC POLICY

It has long been recognized that several important national problems are fundamentally related to the number of miles driven by passenger vehicles. Consumption of gasoline, emission of air pollutants by motor vehicles, and auto-related accidental deaths and injuries are all roughly proportional to VMT. These phenomena, however, also depend on technological parameters -- the average fuel economy of the auto fleet, effectiveness of emission controls, and crash-worthiness of automobiles. Such technological parameters have been viewed historically as the means of achieving national goals.

This perspective must now be reassessed. In 1975, Americans drove about one trillion miles, nearly three times the total for 1950 (Fig. 1). During this 25-year period the problems of auto safety, pollutant emissions, and fuel consumption emerged. Each stimulated legislation regulating the performance of new cars. Technological changes introduced to meet Federal standards have indeed improved crash-worthiness and pollutant emissions, while the new fuel economy standards (1) should have a similar impact. Given the pattern of growth in auto travel, however, it is unclear whether such technological refinements can keep pace. Continually increasing VMT would require ever more stringent performance standards and a series of technological breakthroughs both difficult and expensive to achieve (2). If VMT were to stop growing or decrease unexpectedly, on the other hand, we might pay large sums for more performance than is wanted or necessary.

The problem is further complicated by the interdependence of auto performance and price with VMT. Higher fuel economy levels decrease the costs of driving and could stimulate even larger growth in VMT. Higher prices for refined technology, on the other hand, may reduce new car sales and VMT. Obviously, the efficacy of a combination of regulations on auto performance can be evaluated only after its effects on future levels of VMT are determined.

Finally, it is conceivable -- perhaps likely -- that limitation of VMT will become an explicit public policy in the future. Lowering VMT would decrease our reliance on uncertain technological developments. Everyone favors new mass transportation facilities, but some stimulus will probably be necessary to convince the driving public to switch modes. While several policy instruments might be used, we must be able to analyze their eventual impact on VMT in order to choose the least disruptive and most efficient approach.

All of which points out the need for reasonably accurate and policy sensitive forecasting techniques for VMT. Such techniques are not available, partly because of the complexity of the problem and partly because the central importance of VMT forecasts is only now becoming apparent. There is, however, a substantial literature on previous attempts to analyze and model VMT. The results of previous research provide a useful framework for designing and developing improved models.

## HISTORICAL APPROACHES TO VMT FORECASTING

Previous research on VMT falls into two distinct categories. For some 20 years, urban travel demand has been studied intensively to improve planning for metropolitan transportation facilities. More recently, a limited effort has been made to derive forecasting equations for aggregate national miles of travel by automobiles. While it is impossible to review individual studies here, the work within each category has been similar enough to permit a general characterization of findings.

Models of Urban Travel Demand -- While, strictly speaking, analysis of urban travel demand does not provide forecasts of VMT, it does offer many insights into how a VMT model might be structured. A large number of urban travel demand (UTD) models have been developed; summary descriptions are available in (3) and (4). Figure 2 provides a general overview of the approach.

The principal objective of UTD analysis is to match the capacity of the regional transport network -- largely highways -- to projected traffic flows. Traditionally, four steps have been used to accomplish this goal:

(1) trip generation

(2) trip distribution

(3) modal split

(4) traffic assignment

The traffic assignment from step (4) enables planners to determine whether any links in the system will be overcrowded and how traffic will redistribute itself if new facilities are available.

Empirically estimated relationships are used to determine trip generation and distribution, as well as modal split, based on the land use pattern, population and income levels, and intraregional travel times and costs of the area. Traffic is then assigned to specific links in the network by assuming that the least-cost or least-time routes will be selected. The total number and lengths of trips are implicit in the information generated, so that total vehicle miles of travel could be derived.

State-of-the-art UTD models have several appealing characteristics. Their forecasts are disaggregated by trip purpose, which in principal reflects the varying behavior and responses of people driving for different purposes. They attempt to represent the actions of individual decision-makers and the factors they respond to in day-to-day travel decisions. They explicitly address choices among competing modes of

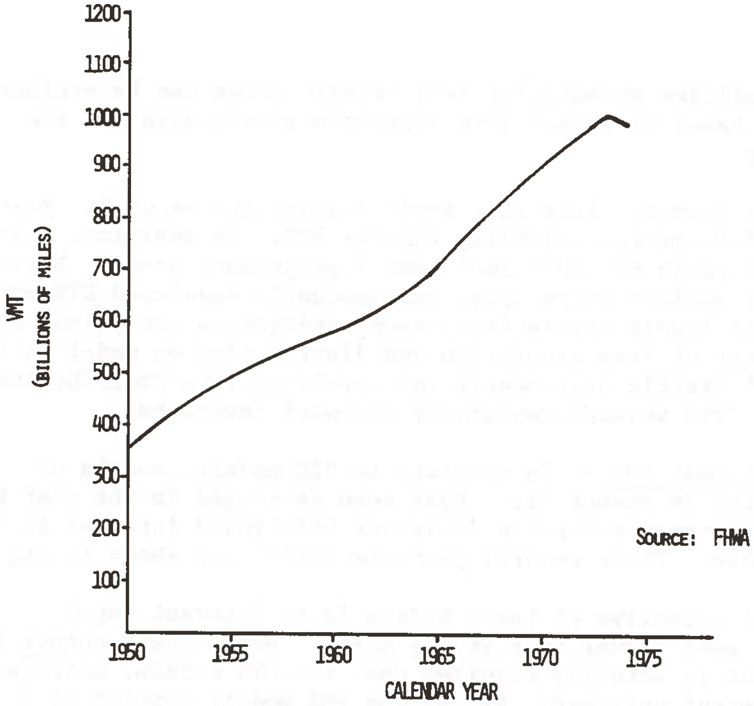

Figure 1. Annual U.S. Vehicle Miles of Travel

| | |
|---|---|
| CENTRAL OBJECTIVE: | MATCHING NETWORK CAPACITY TO TRAFFIC FLOWS |
| STEPS IN ANALYSIS: | (1) TRIP GENERATION<br>(2) TRIP DISTRIBUTION<br>(3) MODAL SPLIT<br>(4) TRAFFIC ASSIGNMENT |
| EXOGENOUS INFLUENCES: | POPULATION AND INCOME LEVELS<br>TRAVEL TIMES AND COSTS<br>LAND USE PATTERN |
| ADVANTAGES: | DISAGGREGATES TRAVEL BY TRIP PURPOSE<br>ATTEMPTS TO REPRESENT INDIVIDUAL DECISION-MAKERS<br>ADDRESSES PROBLEM OF COMPETING MODES<br>ADEQUATE DATA USED FOR SUPPORT |
| DISADVANTAGES: | DOES NOT FORECAST MILES OF TRAVEL<br>IGNORES FEEDBACK AMONG PRINCIPAL VARIABLES<br>APPLICABLE TO SINGLE GEOGRAPHIC AREA |

Figure 2. Urban Travel Demand Models

travel, so that policies stimulating mass transit usage can be evaluated. Finally, they are based on direct home interview survey data for the region in question.

These models, however, have some serious drawbacks as well. Most important is the failure to explicitly address VMT. In addition, their forecasts are applicable to individual, small geographic areas. National or state forecasts would require many, independently developed UTD models. Finally, UTD models ignore interactions among endogenous variables, for example, the effects of trip generation and distribution on modal split and the effects of traffic assignments and levels on trip distribution and modal split. This weakens confidence in model forecasts.

Models of National VMT -- In contrast to UTD models, models of national VMT are few in number (5). Most were developed in the past two years when fuel shortages and price increases heightened interest in VMT as a policy variable. Their general characteristics are shown in Fig. 3.

The principal objective of these models is to forecast total national miles of auto travel on a yearly basis. Hence their output is much closer to what is actually required than the UTD models, which were designed for different purposes. All of the VMT models consist of a single, statistically estimated equation relating auto travel to national demographic and economic variables. These variables are in most cases quite similar. They include level of income, size of the driving-age population (or number of licensed drivers), national economic conditions (e.g., the unemployment rate), and some measure of the cost of driving, often gasoline price.

The advantages of this approach are direct representation of VMT as the dependent variable and the capability of making straightforward national forecasts. They represent, in essence, a first step in the direction of an adequate VMT forecasting ability. Unfortunately, they suffer from a number of interrelated problems which hamper their usefulness.

The most important of these problems are the lack of representation of different types of travel, of competing modes, and of individual behavior. They do not allow analysis of policy effects on different kinds of trips or of policies involving mass transit. They are based on aggregate correlations for the nation as a whole which may not reflect actual cause-and-effect relationships for individual decision-makers.

This simplistic structure can be traced back to the data (6) used in their development. The data are a national time series, undifferentiated by type of travel, and containing highly collinear and serially correlated variables. In this format, representation of the influence of competitive modes of travel is exceedingly difficult. Furthermore, the data are so stable and intercorrelated that statistical results must be viewed with suspicion. In spite of differences in specifications, for example, all of the VMT equations reviewed have coefficients of determination ($R^2$) of 0.99. And the multicollinear explanatory variables suggest that many parameter estimates are biased. Hence the usual performance statistics for regression analysis cannot establish the adequacy of the models.

## DESIGNING AN IMPROVED MODEL

Neither urban transportation demand models nor national VMT models offer the policy-sensitive, accurate forecasting tools now required. Further, it does not seem likely that continued efforts along these historical lines will supply what is missing. While the best UTD models display more realistic and innovative structures, they are geared toward other forecasting objectives. The national VMT models supply more useful projections (for our purposes), but are overly simplistic and biased. Figure 4 compares some important features of the two kinds of models. A synthesis utilizing the advantageous characteristics of both approaches would appear to be necessary.

An improved VMT model, first, should retain a microscale specification and should be supported by microscale data to the greatest possible extent. This would allow the testing of behavioral, cause-and-effect relationships at the level of the individual decision-making unit. Microscale data, in addition, fully represent variability in relationships that is lost through aggregation. While staying at the microscale level, however, the model should be general rather than situation-specific, so that forecasts may be aggregated from the local to state, regional, or national totals. Hence the model should probably be estimated with a national sample of data, but interregional differences in relationships should be represented.

Clearly an improved model must focus on miles of travel as the dependent variable. Since VMT is generated through trip-making, however, the factors which influence trip decisions and variations in influence for different kinds of trips should be represented.

The improved model should be multi-modal, at least to the point of reflecting the influence of competing modes of transportation on auto travel. This is central to designing and evaluating mass transit investment programs.

Finally, the model probably should address yearly rather than shorter term events because they are more stable and simpler to analyze. It should be recognized, however, that this decision strongly influences the specification of relationships. On a day-to-day basis, for example, auto ownership should be a determinant of VMT, while on a yearly basis, demand for travel should be a determinant of auto ownership.

Beyond these basic structural requirements, we must inquire as to the most appropriate theoretical specification for an improved VMT model.

| | |
|---|---|
| Central Objective: | Forecasting total national miles of auto travel |
| Analytic Approach: | Single-equation statistical model |
| Exogenous Influences: | National population and income levels |
| | Costs of auto travel (e.g., gasoline price) |
| | National economic conditions (e.g., unemployment rate) |
| Advantages: | Direct representation of VMT |
| | National forecasting capability |
| Disadvantages: | Does not disaggregate by type of travel |
| | Does not represent competing modes |
| | Does not reflect individual behavior |
| | Poor quality data used for support |
| | Cannot address regional trends and influences |

Figure 3. VMT Models

| Urban Travel Demand Models | VMT Models |
|---|---|
| Microscale (cross sectional) | Aggregate (time series) |
| Situation-specific | General |
| Metropolitan | National |
| Focus on trip-making | Focus on miles of travel |
| Multi-modal | Auto travel only |
| Short-term (daily) events | Long-term (yearly) events |

Figure 4. Historical Approaches

This step has been largely omitted from previous efforts, yet it should play a critical role in econometric model-building. Without careful specification of hypothetical relationships for testing, it is only possible to engage in a posteriori rationalization of results. This procedure encourages statistical fishing to find significant parameters and an "acceptable" coefficient of determination, even though such practices violate many basic rules of statistical analysis.

In principle, as suggested by the UTD models, VMT can be represented as a demand for auto travel in a specification equivalent to demand for other economic goods. The model should include at least three classical economic phenomena: income elasticity, price elasticity, and cross-elasticities for competing goods. The precise fashion in which these phenomena are represented, however, depends on the overall modeling approach taken.

Variables used to reflect income effects on VMT should be different for micro- and macro-level models. Some forms of auto travel (e.g., vacations) are clearly dependent on current levels of disposable income. Other forms (e.g., commuting) should respond to changes in permanent (long term) income levels. On the suggested micro-level, some form of both variables should be tested.

The relevant price of auto travel is cost per mile. In the short run, the only variable cost is that of fuel, which depends on gas price and fuel economy. Over a longer time period, vehicle maintenance would also be a variable cost, and in the long run, the annual cost of owning and operating a car would have to be included. Under any time horizon, the use of gas price alone, without adjustment for fuel economy, leads to bias in the estimation of the price coefficient and the resulting elasticity measure.

Viewing public transit as a substitute good, the choice of a transit variable should be its price. Data on price per mile for transit are seldom available, so that simple proxy measures for the availability of service often must suffice. The difficulty is obtaining data on transit service increases when a macro-view is taken, for there are few meaningful aggregate measures of transit availability.

Other potential substitutes for intercity auto travel include air, rail, and bus transportation services. The average cost per mile for each of these services might also be included in the specification.

In addition to the above economic factors, several geographic and social indices suggest themselves. A density or urbanization variable, for example, would reflect spatial distances over which travel must occur. The availability of good roads on which to drive should influence demand for auto travel, and represents a potential policy variable as well. On the micro-level, form of employment and household size might also affect demand.

A final, crucially important issue for the specification is the relation of auto travel decisions to other household choices. Of immediate concern are auto purchases and ownership, which in turn raise questions about new and used car sales and scrappage of used cars. More generally, household choices about where to live and work clearly affect and are affected by auto travel and ownership decisions. Interactions between these choices should be incorporated.

Many of the above mentioned factors have been omitted in previous modeling efforts. Such omissions cause "underspecification" and can bias the coefficients of variables included in the model unless all explanatory factors are perfectly independent. This condition seldom occurs in practice, so we have an additional reason to believe that existing models contain biased parameters.

Figure 5 summarizes the principal characteristics of the "optimal" VMT model. It would offer forecasts at several geographic levels of aggregation. It would represent alternative types of trips after factors that influence them at the level of individual decision-making units. It would be based upon a rigorous theoretical specification embodying classical demand mechanisms and representing interactions among several important variables. Since it would be "optimal," the model would have all the advantages and none of the disadvantages of previous UTD and national VMT models.

Naturally, however, a truly optimal socioeconomic model is impossible to develop. The behavioral relationships involved are transitory and probabilistic rather than permanent and deterministic. There are, in addition, some major practical problems hindering development of an improved VMT model.

## PROBLEMS IN MODEL DEVELOPMENT

By far the greatest problem in developing an improved VMT model is the lack of adequate data. Previous research has relied on metropolitan home-interview surveys that are situation specific or aggregate national information. There is no up-to-date, nationally representative, micro-level data base to support more realistic model specifications.

There is, further, a serious problem in obtaining direct measurements of auto travel even in a limited sample. Odometer readings are possible, but they must continue over an extended time period, while the purchase and sale of vehicles is also recorded. Relying on mileage reports from individuals or households creates inaccuracies and uncertainty in the data base.

Because of insufficient data, it is not possible to test a truly complete specification, even if we could design one. Some of the causal factors mentioned above cannot be measured with sufficient accuracy to allow tests of their influence on VMT. Others may prove to have

**CENTRAL OBJECTIVE:** FORECASTING REGIONAL AND NATIONAL VMT FOR POLICY ANALYSIS

**ANALYTIC APPROACH:**

(1) REPRESENT DIFFERENT TYPES (PURPOSES) OF TRAVEL SEPARATELY

(2) USE CHARACTERIZATION OF INDIVIDUAL DECISION-MAKERS TO PREPARE AGGREGATE FORECASTS

(3) INCLUDE CLASSICAL DEMAND MECHANISMS:

- INCOME LEVELS (CURRENT AND PERMANENT)
- PRICE OF AUTO TRAVEL (COSTS OF DRIVING)
- PRICES OF COMPETING MODES
- SUPPLY CONSTRAINTS (AUTO OWNERSHIP AND NETWORK CAPACITY)
- EXOGENOUS SOCIOECONOMIC FACTORS (DEMOGRAPHY, ECONOMIC CONDITIONS)

(4) INCORPORATE FEEDBACK AND SIMULTANEITIES AMONG

- DEMAND FOR TRAVEL
- AUTO OWNERSHIP/DEMAND
- NEW AND USED CAR SALES
- AUTO SCRAPPAGE

**ADVANTAGES:** ALL

**DISADVANTAGES:** NONE

Figure 5. Optimal Model of Auto Travel

insignificant effects when empirically tested. Nevertheless, parameters ultimately included in the model can be evaluated only after the most thorough possible specifications have been tested. Future modeling efforts should therefore begin with complex specifications to ensure that the simplification which occurs in the normal course of hypothesis testing does not bias model coefficients.

Model development is also hampered by uncertainties in the appropriate theoretical specification. We do not know, for example, whether demand for auto travel is basic or whether it is derived from demand for automobiles. Most existing models implicitly assume the latter, although it seems more likely that demand for travel, arising from needs for commuting, shopping, recreation, etc., determine auto-ownership decisions in the long run.

Similarly, the system of simultaneously interacting variables, of which VMT is a part has not been adequately analyzed in the past. Model specifications that incorrectly represent such relationships will lead to biased or inaccurate parameter estimates. Unfortunately, we have little information to guide specifications in the right direction. Clearly, such theoretical uncertainties can be resolved only through empirical testing of alternative hypotheses. Yet such tests, fundamental as they are, deserve better data than are currently in use. And this returns us to the original problem.

Until alternative data reflecting more of the true variability in VMT are analyzed, the appropriate theoretical questions and alternative specifications cannot be adequately tested. It might be argued with some justification that problems in the current state-of-the-art result from the lack of adequate data for more thorough analysis. To a certain extent this is true; it is also true, however, that better use can be made of what information does exist. Collection of an adequate set of data is an important longer-term goal.

## CONCLUSIONS

Reliable forecasts of vehicle miles of travel by private passenger vehicles is an increasingly important input to national policy-making. Not only is VMT a fundamental determinant of fuel consumption, air quality, and auto-related deaths and injuries, but it also is a policy variable in its own right. Direct or indirect limitations on VMT could become a necessary element in future policy.

Currently available techniques for forecasting VMT are overly simplistic and do not represent potential effects of public policies on auto travel. The literature, however, suggests that an improved VMT model can be designed by synthesizing a new specification from previous lines of research.

Before such a model can be developed, however, fundamental studies are necessary to determine what factors influence household decisions concerning auto travel, and how those decisions interact with others like auto-ownership and residential location.

Many such studies can be supported by currently available data. In order to even approach the optimal model structure and specification, however, an up-to-date, nationally representative sample of household data is urgently required.

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# EVALUATION OF DRIVER AID DEVICES FOR IMPROVED FUEL ECONOMY

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## ABSTRACT

It is the purpose of this effort to survey and evaluate the characteristics of the various driver aid devices which have been postulated to offer improved vehicle fuel economy; to determine which class of devices has the best potential for improving fuel economy; and to identify meaningful control variables or other factors which should be considered in structuring a test program for experimental verification of the fuel economy improvement potential of driver aid devices. The study addresses driver aid devices within the general classes of vacuum gages, fuel flowmeters, engine speed monitors, vehicle speed monitors, and throttle position monitors.

This paper discusses the current status of the program. Principal emphasis is devoted to characterizing the available devices in terms of their features and operating principles. The available fuel economy test data for such devices are summarized. Similar test data for drivers who have received training only (no auxiliary or aid devices) are reviewed for comparison purposes.

## DISCUSSION

### 1. Devices Considered and Method of Approach

The specific types of driver aid devices considered included:

a. manifold vacuum gages
b. miles per gallon or MPG meters
c. an active driver feedback system which operates on the accelerator pedal
d. accelerometers
e. pyrometers
f. speed-warning devices
g. throttle position devices
h. automatic cruise controls
i. fuel flowmeters and totalizers
j. speedographs and tachographs

For these devices, the available literature was first reviewed. Then, data was acquired from auto makers, government agencies, and industrial companies. Based on these data, the available devices and techniques were characterized and their operating principles analyzed. Where appropriate, possible side effects (e.g., safety considerations) occasioned by the use of such devices were examined.

### 2. Fuel Economy vs. Driving Habits

The interest in driver aids stems in large measure from the effect of driving habits on fuel economy. Table 1 summarizes available data concerning this impact.

The Shell, Mobil, and TSC/NHTSA tests shown were all directed to determining the impact of driver training, and each program used a single car over a designated test route, but with a multiplicity of drivers; 23 for Shell, 20 for Mobil, and 20 for TSC. The Shell program stressed coaching in gas-saving techniques; Mobil merely provided a driving instruction manual for reading; and the TSC program involved a one-hour training session. These three test programs indicated fuel economy improvements from 8.9 percent to 15 percent for these driver training methods. In the Mobil test, a second series of tests with a vacuum gage, after reading the manual, produced an additional 1 percent improvement.

The Douglas program is a more comprehensive program dealing with fleet drivers only. They are not only given instruction in driving techniques, but also training in vehicles equipped with various driver aids. Douglas reports a 22 percent improvement with a 15-driver test group. The two auto club tests shown, Southern California and Michigan, were made to illustrate the effects of "bad" rather than "good" driving habits, and tend to show that high accelerations and excessive speeds can result in fuel economy penalties from 12 to 44 percent, depending upon the degree of "bad" driving and the driving route.

Although the data base is limited, these tests indicate a potential for 10 to 15 percent improvement in fuel economy due to fuel-efficient driving habits. The auto club data tends to indicate excessive acceleration is a principal factor in poor fuel economy. Thus, the interest in driver aids is twofold; first, as a device to aid in driver training, and second, as an aid to "remind" a trained driver when he tends to return to poor driving habits.

### 3. Acceleration vs. Fuel Economy

Figure 1 depicts calculated results for a small car which is accelerating from a standing start to 40 mph steady-state cruise speed at 3 acceleration levels: mild (.05 g), moderate (.10 g), and brisk (.15 g). The curves represent cumulative fuel economy vs. distance traveled.

For short distances, 0.1 to 0.2 miles, the fuel economy loss due to "brisk" acceleration is quite evident; whereas the mild and moderate acceleration levels are similar. For longer distances, < 0.2 mile, the "moderate" acceleration results in the best cumulative fuel economy, principally because the favorable 40 mph cruise condition is reached in a shorter time and distance. This, of course, is an isolated and idealized case. What is important is the role of acceleration during the speed and traffic conditions encountered in everyday driving.

TABLE 1. FUEL ECONOMY VS. DRIVING HABITS – TEST RESULTS

| COMPANY/AGENCY | PURPOSE OF TEST | RESULTS OF TEST |
|---|---|---|
| SHELL OIL COMPANY | IMPROVEMENT DUE TO COACHING IN GAS SAVING TECHNIQUES (23 drivers, 1 car, 22.3 mile course) | 8.9% IMPROVEMENT OVER WELL-TUNED CAR WITH RADIALS |
| AUTO CLUB OF SOUTHERN CALIFORNIA | DETERMINE EFFECT OF ACCELERATION LEVELS (1 driver, 20 cars, 1/4 mile, standing start to 40 mph speed) | 12.4% LOSS DUE TO "MODERATE" ACCELERATION<br>27.2% LOSS DUE TO "HEAVY" ACCELERATION |
| MOBIL OIL CORP. | IMPROVEMENT DUE TO READING DRIVING INSTRUCTION MANUAL (20 drivers, 1 car, 18 mile course) | 15% IMPROVEMENT |
| | EFFECT OF USING VACUUM GAGE AFTER READING MANUAL (8 drivers, 1 car, 18 mile course) | 1% IMPROVEMENT OVER 15% ACHIEVED BY READING ONLY |
| AUTO CLUB OF MICHIGAN | DETERMINE EFFECT OF BAD DRIVING HABITS AS COMPARED TO GOOD DRIVING TECHNIQUES (22.8 mile commuter route, 10 mile expressway route, 1 car) | 44% LOSS DUE TO BAD DRIVING ON COMMUTER ROUTE<br>23% LOSS DUE TO BAD DRIVING ON EXPRESSWAY ROUTE |
| DOUGLAS AIRCRAFT COMPANY | DETERMINE IMPACT OF DRIVER TRAINING PROGRAM ON FLEET DRIVERS. INSTRUCTION IN DRIVING TECHNIQUES AND TRAINING IN VEHICLES EQUIPPED WITH MPG METER, VACUUM GAGE, PYROMETER (15 driver test group) | 22.1% IMPROVEMENT DUE TO TRAINING PROGRAM WITH 15 DRIVERS |
| TSC/NHTSA | PILOT TEST TO DETERMINE IMPACT OF TRAINING (10 drivers with no training, 10 drivers with 1 hour training, 9 mile route, 1 car) | ~10% IMPROVEMENT FOR DRIVER WITH 1 HOUR OF TRAINING |

- ACCELERATE-TO-CRUISE-SPEED CASE
  - SMALL CAR, MANUAL TRANSMISSION
  - STANDING START TO 40 mph STEADY STATE CRUISE SPEED
  - THREE ACCELERATION LEVELS
    - MILD = 0.05 g
    - MODERATE = 0.10 g
    - BRISK = 0.15 g (carburetor power enrichment throughout much of engine speed and load range)
  - FUEL CONSUMED IS INITIALLY GREATER FOR MODERATE (0.10 g) vs MILD (0.05)
  - CUMULATIVE MPG FOR 0.10 g EXCEEDS 0.05 CASE
    - FAVORABLE 40 mph CRUISE CONDITION REACHED IN SHORTER TIME AND DISTANCE
  - EXTREME ACCELERATION FUEL PENALTY FOR 0.15 g CASE REVERSES TREND

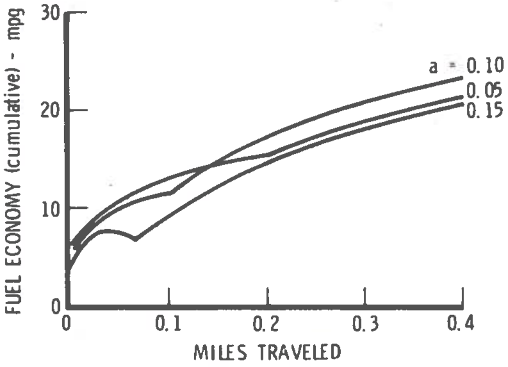


Figure 1. Acceleration Vs. Fuel Economy

Table 2 shows acceleration vs. fuel economy results from tests conducted by the Los Angeles Police Department. An intermediate-size patrol car was equipped with an intake manifold control device to maintain the three fixed vacuum levels shown in the figure. Based on tests over a 100-mile city test segment, "flooring" the gas pedal to accelerate caused a 32 percent reduction in fuel economy from that obtained with the "normal traffic flow" vacuum level. The gain in fuel economy due to "mild" acceleration (10 in. Hg vacuum) was nearly 18 percent.

## 4. Speed vs. Fuel Economy

Figure 2 illustrates the effect of speed on fuel economy for two vehicles of different size; a standard and a compact. During steady-state cruise speeds (the top curve in each case), fuel economy is principally related to car size and weight, engine size, accessories used, etc. The driver only has the option of selecting the most economical cruise speed when traffic conditions permit.

During cyclic driving conditions, for a given car, the fuel economy is a function of the number of stops and starts, rates of acceleration and deceleration, idling time, etc. The driver has some control over these factors through good driving techniques; however, traffic conditions do limit the degree of control.

## 5. Driver Aid Device Characteristics

### 5.1 Manifold Vacuum Gages

Some typical face design variations for manifold vacuum gages are illustrated in Figure 3. They range from the standard vacuum gage, which provides a direct readout in in. Hg, to a colored range readout, which does not require specific knowledge on the part of the driver of economical vacuum levels. The other type of device shown in the figure is the Accelerite, a linear piston gage with two colors. According to the manufacturer's instructions shown, when the piston color is yellow (vacuum

## TABLE 2. ACCELERATION VS. FUEL ECONOMY

0 LOS ANGELES POLICE DEPARTMENT TESTS

/ INTERMEDIATE-SIZE PATROL CAR WITH 401 CID ENGINE

/ 100-MILE CITY TEST SEGMENT

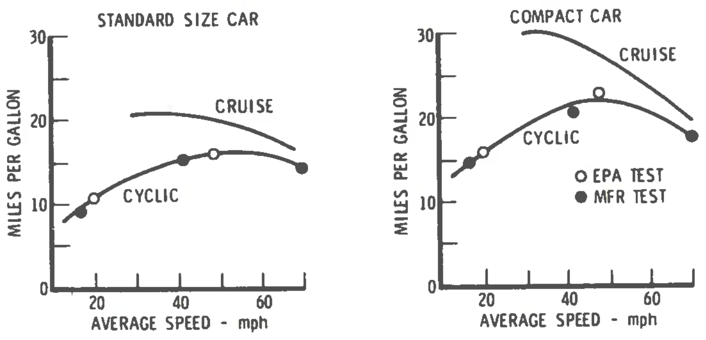
/ INTAKE MANIFOLD CONTROL DEVICE TO MAINTAIN THREE FIXED ACCELERATION LEVELS

| Vacuum Level (in. Hg) | Acceleration Level | Fuel Economy (mpg) | Relative Fuel Economy |
|---|---|---|---|
| 10 | Mild | 14.7 | 1.176 |
| 5 | Normal Traffic Flow | 12.5 | 1.0 |
| ~ 0 | Maximum | 8.5 | 0.68 |

/ "FLOORING" GAS PEDAL TO ACCELERATE CAUSED 32 PERCENT REDUCTION IN FUEL ECONOMY

/ GAIN IN FUEL ECONOMY DUE TO MILD ACCELERATION WAS NEARLY 18 PERCENT

o LIKELY A CUMULATIVE ONE RESULTING FROM FEWER TENDENCIES TO OVER-ACCELERATE, OVER-DECELERATE, AND BRAKE EXCESSIVELY UNDER THE STOP-AND-GO TRAFFIC CONDITIONS



- STEADY STATE CRUISE SPEEDS
  - FUEL ECONOMY IS FUNCTION OF CAR SIZE AND WEIGHT, ENGINE SIZE, ACCESSORIES, etc
  - DRIVER ONLY HAS OPTION OF SELECTING ECONOMICAL CRUISE SPEEDS WHEN TRAFFIC CONDITIONS PERMIT

- CYCLIC DRIVING CONDITIONS
  - FUEL ECONOMY, FOR GIVEN CAR, FUNCTION OF NUMBER OF STARTS AND STOPS, RATES OF ACCELERATION AND DECELERATION, IDLING TIME, etc.
  - DRIVER HAS SOME CONTROL OVER ACCELERATION, DECELERATION, AND BRAKING THROUGH GOOD DRIVING TECHNIQUES
    - TRAFFIC CONDITIONS AGAIN LIMIT DEGREE OF CONTROL

Fugure 2. Speed Vs. Fuel Economy

levels above approximately 10 in. Hg), the engine system is operating economically. When the piston color is blue (vacuum levels below the 5 to 10 in. Hg range), fuel economy is adversely affected.

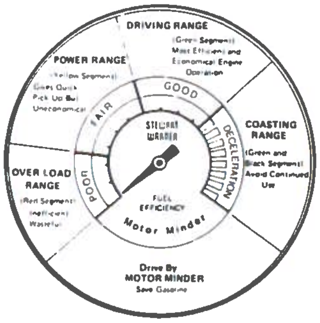
Table 3 summarizes the characteristics of these three devices, as well as multiple colored lights and single-light systems. The multiple-light system has colored lights corresponding to best, good, fair, and poor fuel economy conditions. The single-light system is preset to warn the driver when the vacuum level falls below 5 to 10 in. Hg.

The actions and/or knowledge required of the driver vary with the type of gage. With a dial readout gage, the driver must know that high vacuum readings generally indicate fuel-efficient operation, and that readings below approximately 10 in. Hg indicate excessive acceleration. With a color range readout or multiple colored lights, the driver merely attempts to stay in the best fuel economy "zone" or "light" area by controlling accelerator pedal pressure. With the single-light system, pedal pressure must be reduced if the light comes on. In the case of the linear piston device, pedal pressure must be controlled to keep the piston color yellow.

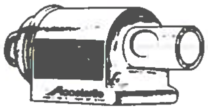
The available test data for manifold vacuum gages are shown in Table 4. The Econ-O-Lite, a flashing light unit, was tested by the Pastal Service on seven half-ton and quarter-ton trucks, with three of the trucks having a fuel economy improvement. Employees of a Detroit TV station tested their personal cars (Pontiac, Ford, and Plymouth) with factory-equipped vacuum gages, and noted improvements from 6.9 to nearly 25 percent in fuel economy. Most of the available data concern the Accelerite, the two-color linear piston vacuum gage. As can be noted in Table 4 fuel economy improvements for this device ranged from 3 to 17 percent.

It should be emphasized that all of the data shown in Table 4 are based on very limited tests, and that it is impossible to separate out the effects of the vacuum gage and any driving instructions that may have been

STANDARD VACUUM GAGE



COLORED RANGE READOUT



ECONOMY RANGE

WHEN YELLOW "ECONOMY RANGE" SIGNAL SHOWS, YOUR ENGINE CARBURETOR SYSTEM IS OPERATING ECONOMICALLY. YOU ARE GETTING MAXIMUM GASOLINE MILEAGE

POWER RANGE

WHEN BLUE POWER RANGE SIGNAL SHOWS, YOUR CARBURETOR POWER SYSTEM RANGE IS AT WORK AND CONSUMPTION OF GASOLINE CAN BE UP TO TWICE THE ECONOMY RANGE, CAUSING AN ENERGY WASTE

ACCELERITE VACUUM DEVICE

Figure 3. Manifold Vacuum Gages — Face Design Variations

TABLE 3. MANIFOLD VACUUM DEVICES — CHARACTERISTICS SUMMARY

COST RANGE OF $5 TO $35

| TYPE OF DEVICE | TYPE OF AID PROVIDED TO DRIVER | ACTIONS AND/OR KNOWLEDGE REQUIRED OF DRIVER |
|---|---|---|
| ● DIAL READOUT, in. hg. | CONTINUOUS DISPLAY OF VACUUM OVER ALL DRIVING CONDITIONS | KNOW THAT HIGH VACUUM READINGS GENERALLY INDICATE FUEL-EFFICIENT OPERATION; KNOW THAT READINGS BELOW ~10 in. hg. INDICATE EXCESSIVE ACCELERATION. MUST MONITOR GAGE AND REDUCE PEDAL PRESSURE TO MAXIMIZE READINGS |
| ● COLOR RANGE READOUT | MULTIPLE COLORED ZONES ON DIAL REPRESENTING POOR, FAIR, AND GOOD ECONOMY ZONES, AND A DECELERATION ZONE | ATTEMPT TO STAY IN BEST FUEL ECONOMY ZONE OR LIGHT AREA DURING GIVEN DRIVING SITUATION BY REDUCING PEDAL PRESSURE TO REDUCE ACCELERATION AND/OR DECREASE SPEED |
| ● MULTIPLE COLORED LIGHTS | COLORED LIGHTS CORRESPONDING TO BEST, GOOD, FAIR, AND POOR FUEL ECONOMY | |
| ● SINGLE LIGHT (continuous or flashing)<br>• DASH-MOUNTED<br>• FENDER-MOUNTED | LIGHT SYSTEM PRESET TO WARN DRIVER WHEN VACUUM FALLS BELOW 5 TO 10 in. hg. AND INDICATE EXCESSIVE ACCELERATION | REDUCE PEDAL PRESSURE UNTIL LIGHT TURNS OFF |
| ● TWO-COLOR LINEAR PISTON READOUT | LINEAR PISTON PRESET TO CHANGE IN COLOR FROM YELLOW TO BLUE WHEN VACUUM FALLS TO 5 TO 10 in. hg. AND INDICATE EXCESSIVE ACCELERATION | REDUCE PEDAL PRESSURE UNTIL PISTON COLOR IS YELLOW |

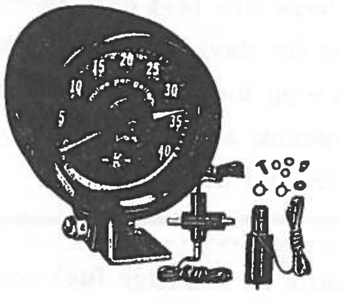
TABLE 4. MANIFOLD VACUUM DEVICES – TEST DATA

| DEVICE | TESTED BY | VEHICLE | FUEL ECONOMY RESULTS |
|---|---|---|---|
| ECON-O-LITE | POSTAL SERVICE | ONE 1/2 ton TRUCK<br>SIX 1/4 ton TRUCKS | ~0.1 mpg IMPROVEMENT<br>~1.0 mpg IMPROVEMENT FOR 2 OF 6 TRUCKS |
| PONTIAC VACUUM GAGE | EMPLOYEES OF WWJ-TV DETROIT | PONTIAC | 6.9% IMPROVEMENT |
| FORD VACUUM GAGE |  | FORD | 24.6% IMPROVEMENT |
| PLYMOUTH FUEL PACER |  | PLYMOUTH | 23.1% IMPROVEMENT |
| ACCELERITE | RYDER TRUCK LINES |  | 10.2% IMPROVEMENT |
|  | POSTAL SERVICE | ONE 1/2 ton TRUCK<br>ONE 1/2 ton TRUCK | 3% IMPROVEMENT<br>7% IMPROVEMENT |
|  | S.V. SHELTON, GEORGIA INSTITUTE OF TECHNOLOGY | 5 VEHICLES | 11.37% AVERAGE IMPROVEMENT (between 8.5 and 13.6% with 95% confidence level) |
|  | CITY OF JACKSONVILLE, FLORIDA | FIVE 1/2 ton TRUCKS | 17% IMPROVEMENT |
|  | NATIONAL PARK SERVICE | FOUR VEHICLES | 10% IMPROVEMENT |

- ABOVE TESTS ALL VERY LIMITED
- IMPOSSIBLE TO SEPARATE OUT EFFECTS OF DEVICE AND INSTRUCTIONS
- MOTIVATION MAY BE EXTREMELY IMPORTANT FACTOR
  - MORE NEGATIVE RESULTS INVOLVED FLEET VEHICLES

## Miles-Per-Gallon (MPG) Meter

- TYPE OF AID PROVIDED
  - DIRECT READOUT OF VEHICLE FUEL ECONOMY (mpg) DURING DRIVING CONDITIONS
- ACTIONS AND/OR KNOWLEDGE REQUIRED BY DRIVER
  - DRIVER MUST SCAN INSTRUMENT AND ADJUST VEHICLE SPEED AND/OR ACCELERATION TO OBTAIN HIGHEST MPG READING CONSISTENT WITH DRIVING CONDITIONS OR DESIRES
  - DRIVER NEEDS TO KNOW BASIC SPEED vs FUEL ECONOMY RELATIONSHIP TO FULLY APPRECIATE MPG READINGS IN LOWER PORTION OF SPEED RANGE (< 30 mph)



MILES-PER-GALLON METER

- MANUFACTURERS
  - SPACEKOM
  - FLOWSCAN
- COST
  - $39 TO $150
- NO AVAILABLE TEST DATA

Figure 4. Miles-Per-Gallon (MPG) Meter

given to the drivers. It is felt that motivation, on the part of the driver, may be an extremely important factor in such tests. In this regard, it should be noted that some of the lower or more negative results shown in Figure 7 involved fleet vehicle drivers.

## 5.2 Miles-Per-Gallon (MPG) Meter

The miles-per-gallon or MPG meter is shown in Figure 4 . It provides a direct readout of vehicle fuel economy during driving conditions (by measuring both the speed of the car and fuel flow rate). To use this device, the driver must scan the instrument and adjust vehicle speed and/or acceleration to obtain the highest mpg reading consistent with driving conditions. There is no available vehicle test data for this device.

## 5.3 Active Driver Feedback System

This device is the TEST Gas Saver. It consists of a vacuum-operated bellows on the throttle linkage which offers increased resistance to accelerator pedal movement when engine vacuum levels are low (high vehicle acceleration rates or high power demand). The driver must appreciate what the increased pedal resistance implies, and that the unit can and should be overridden in driving situations where safety conditions dictate the use of increased acceleration and/or speed.

There are test data from two sources. The U. S. Postal Service installed the device on five quarter-ton trucks. One truck achieved a 5.1 percent mpg increase; four trucks decreased in fuel economy from 2.3 to 25.3 percent; and a baseline control truck without the device showed no change in fuel economy.

The device manufacturer has tested the device on seven automobiles and claims an average fuel economy improvement of 20.6 percent.

## 5.4 Accelerometers

Table 5 summarizes the characteristics of two basic accelerometer types. One provides a direct readout of vehicle acceleration, in g's.

TABLE 5. ACCLEROMETERS (1)

| TYPE OF DEVICE | TYPE OF AID PROVIDED TO DRIVER | ACTIONS AND/OR KNOWLEDGE REQUIRED OF DRIVER |
|---|---|---|
| o UNIT CALIBRATED IN G'S (2) | DIRECT INDICATION OF VEHICLE ACCELERATION IN G'S | MUST SCAN READOUT, HAVE KNOWLEDGE OF G LEVELS ACCEPTABLE FOR ECONOMICAL OPERATION, AND ADJUST PEDAL PRESSURE TO AVOID EXCESSIVE G VALUES |
| o UNIT WITH GREEN, YELLOW, AND RED LIGHTS (3) | COLORED LIGHTS INDICATING LOW, MEDIUM, AND HIGH ACCELERATION RATES | MUST MODULATE PEDAL PRESSURE TO KEEP LIGHT ON (GREEN) THAT INDICATES LOW ACCELERATION RATE |

(1) NO AVAILABLE TEST DATA

(2) AVAILABLE UNITS:
AUTOTRONIC'S DYNAMIC DYNAMOMETER, $139
SPACEKOM ACCELEROMETER, $39.50

(3) AUTOTRONIC'S MODEL 702 PACESETTER (OR ELECTRONIC POWER INDICATOR); NOT YET IN PRODUCTION

The driver would have to scan the readout and have knowledge of acceptable g levels for economical operation. The second device, not yet in production, has colored lights representing low, medium, and high vehicle acceleration rates. With this device, the driver would attempt to keep the green light on for best fuel economy.

There are no available vehicle test data for accelerometers.

### 5.5 Pyrometers

Pyrometers provide a direct dial readout of exhaust gas temperature. Their use is presently limited to commercial fleet operators, most commonly in diesel engine applications. The driver must scan the readout, and is generally instructed to maintain the temperature reading within a 700°F to 1200°F band by adjusting accelerator pedal pressure. The low temperature limit represents inefficient low-speed operation, while the maximum temperature limit represents excessive engine loads or speeds.

There are no available vehicle test data for pyrometers. They are not marketed as a driver-aid, per se, and no numerical claims are made in the literature.

### 5.6 Other Driver Aid Devices

Table 6 summarizes the characteristics of a number of other driver aid devices. They include:

a. vehicle speed warning devices which notify the driver with a light and/or audio signal when a preset speed level is reached

b. throttle position devices which permit the driver to set the throttle to maintain a desired cruise speed on a level road

c. automatic cruise controls which command a throttle position to attain a preset desired cruising speed

d. fuel flowmeters which provide a direct indication of the rate at which fuel is being used

e. flow totalizers which read out the total gasoline used in a checked interval

## TABLE 6. OTHER DRIVER AID DEVICES – CHARACTERISTICS SUMMARY

| CLASS AND TYPE OF DEVICE | TYPE OF AID PROVIDED TO DRIVER | ACTIONS AND/OR KNOWLEDGE REQUIRED OF DRIVER |
|---|---|---|
| o Vehicle Speed Devices<br>/ Speed Warning<br>- Red Light<br>- Audible buzzer or siren<br>- Green, amber, and red lights with siren<br>- Flashing turn signals<br>(cost range: $10 to $30) | Notifies driver with light and/or audio signal when preset speed level has been reached. | Driver must reduce pedal pressure until sound or light goes off. If unit preset for fuel economy, driver must know economical cruise speed range. |
| o Throttle Position Devices<br>/ Mechanical Hand Throttle<br>/ Electronic preset device<br>(cost range: $2 to $20) | Permits driver to set throttle for desired cruise speed on a level road. | Driver must set device and release or override it when traffic conditions demand (by touching brake pedal or pressing down on accelerator). |
| o Automatic Cruise Controls<br>/ Vacuum-operated<br>/ Electronic-operated<br>(cost range: $90 to $112) | Permits driver to preset a desired cruising speed; device then automatically commands throttle position to attain that speed. | |
| o Fuel Flow Devices<br>/ Flowmeters | Direct indication of rate at which fuel is being used. | Scan instrument and adjust vehicle speed and/or acceleration to obtain minimum fuel flow consistent with driving condition or need. |
| / Flow Totalizer | Reads out total gasoline used in checked interval. Permits driver to compare speeds, routes, etc. | Requires reading indicator at end of trip, recording results, and resetting for next trip. |
| o Recording Devices<br>/ Speedographs<br>/ Tachographs<br>(cost range: $89 to $372)* | Provides continuous recording of driving behavior (vehicle speed, distance, etc. versus time base). Provides no aid to driver during present trip. Used to illustrate driving deficiencies and demonstrate where improvements are needed. Used in fleet-type operations. | None |

*Varies with number of parameters recorded and number of days per recording.

f. speedographs and tachographs which provide a continuous recording of driving behavior. These units are used primarily by fleet operators to illustrate driving deficiencies to the fleet drivers.

## 5.7 Application Summary

Table 7 summarizes the areas of application for the drivers aid devices previously described. The principal areas are acceleration and cruise speed control.

Those devices affording some measure of acceleration control include vacuum gages, MPG meter, the active driver feedback system, the accelerometer, the pyrometer, and the fuel flow meter. The MPG meter and the fuel flow meter capability is considered limited because of the need to carefully scan the instrument to determine variations in readings. The capability of the pyrometer is considered limited because of poor correlation between exhaust gas temperature and fuel consumption rates under various driving conditions.

Those devices affording economical cruise speed control include the MPH meter, throttle position devices, automatic cruise controls, and the fuel flow meter. The pyrometer, speed warning devices, and most vacuum gages also offer the potential for limited cruise control.

The fuel totalizer and speedographs and tachographs do not offer direct control in either of these areas. The totalizer's value lies in record-keeping and comparison functions. Speedographs and tachographs may be extremely valuable as driver training aids.

## SUMMARY

In summary, the following points should be emphasized.

1. The available driver-training-only test data show the potential for a 10 to 15 percent improvement in fuel economy due to improved driving habits. Data from manifold-vacuum device tests show a

similar potential for fuel economy improvement. However, the data base is poor in all reported cases, with a very small sample size.

2. These improvements in fuel economy result from driving habit alterations, not the aid device. However, those devices which enable a driver to consistently refrain from excessive vehicle acceleration rates appear to offer the most potential.

3. Costs which may be involved are not limited to the aid device, per se. While a vacuum gage, for example, may be relatively inexpensive, the costs associated with training and education have not been quantified.

4. Field evaluation tests are necessary to more accurately quantify the fuel savings to be expected and to quantify associated education, training, and implementation costs.

TABLE 7. DRIVER AID DEVICES-AREAS OF APPLICATION SUMMARY

| CLASS AND TYPE OF DEVICE | AREAS OF APPLICATION | | |
|---|---|---|---|
| | ACCELERATION CONTROL | CRUISE CONTROL | OTHER |
| ● MANIFOLD VACUUM GAGES<br>• DIAL AND COLOR RANGE READOUTS, MULTIPLE COLORED LIGHTS | YES | YES (limited) | DIAL READOUT CAN INDICATE ENGINE CONDITION |
| • SINGLE LIGHT, TWO-COLOR LINEAR PISTON | YES | NO | |
| ● MPG METER | YES (limited) | YES | |
| ● ACTIVE DRIVER FEEDBACK | YES | NO | |
| ● ACCELEROMETER | YES | NO | |
| ● PYROMETER | YES (limited) | YES (limited) | |
| ● SPEED WARNING DEVICES | NO | YES (limited) | |
| ● THROTTLE POSITION DEVICES | NO | YES | |
| ● AUTOMATIC CRUISE CONTROLS | NO | YES | |
| ● FUEL FLOW METER | YES (limited) | YES | |
| ● FUEL TOTALIZER | NO | NO | RECORD-KEEPING OF FUEL USED; COMPARISONS |
| ● SPEEDOGRAPHS AND TACHOGRAPHS | NO | NO | DRIVER TRAINING AID |

# AUTOMOBILE MARKET DYNAMICS

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## ABSTRACT

The objective of the study is to forecast responses by consumers and automobile manufacturers to government actions to reduce gasoline use. The time frame of interest is 1976-1980. The product of this study will be estimates of the effect of these government actions on automobile sales by size class and domestic versus foreign market shares.

Four scenarios were developed: (1) base case, (2) gasoline tax, (3) excise tax on new cars, and (4) government regulation of domestic manufacturers.

Under the base case, we make assumptions about the factors relevant to automobile buying, in the absence of the specific government intervention. For example, in the base case we assume the gas is 75¢ a gallon. In the gasoline tax scenario, the gasoline tax is expected to rise in 5¢ per gallon increments through a 95¢ per gallon price in 1979. Under the excise tax scenario, excise taxes are instituted in 1978 on the heavier cars. The tax increases progressively for cars with poor gasoline mileage.

Finally, in the regulation scenario, it is assumed that the manufacturers will be impelled by statute to achieve sales-weighted miles per gallon averages beginning with a minimum of 19 mpg for 1978 through 21 mpg by 1980.

The study assesses technological changes and other factors which can be expected to interact with consumer decisions on which cars to buy. Scenarios were developed in detail. Considered were possible government actions and manufacturer reactions. Estimates were also made, based on economic theory of likely consumer reaction. Consumer questionnaires were developed to determine consumers reaction under each of these scenario conditions. Two series of consumer interviews will be conducted, one of 200 interviews and another of 700 interviews. Finally, a model of automobile replacement and sales will be devised, to calculate the end product estimates from the data obtained from consumers.

# RESOURCE ACCOUNTING FOR ADVANCED VEHICLE SCENARIOS, TASK FORCE ON MOTOR VEHICLE GOALS BEYOND 1980

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Charles Stark Draper Laboratory, Inc.
Cambridge MA

## ABSTRACT

Resource impact has been a major concern in the evaluation of advanced vehicle scenarios in support of the Task Force on Motor Vehicle Goals Beyond 1980. Computer models have been developed or acquired to accomplish accounting for the utilization of material resources, energy and fuels, labor, and capital. Input-output techniques have been used to evaluate labor and capital impacts not just in the motor vehicle industry, but throughout the economy. In particular, the production of lighter automobiles with alternative engine technologies implies a number of significant structural changes in the economy. This presentation will explain the evaluation methodology and review the major results.

# MEASUREMENT OF AUTOMOBILE FUEL ECONOMY AS A FUNCTION OF CHANGES IN SUBSYSTEMS AND DUTY CYCLES

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## ABSTRACT

In addition to previous efforts involving tests on standard size vehicles and the assessment of technological improvements to automobile fuel economy, this program has investigated vehicle characteristics during road and laboratory tests.

Several subcompact vehicles were selected for study; these vehicles reflected both domestic and foreign vehicle production. The engines were evaluated throughout their operating range on test stands. Measurements of fuel consumption and torque were made during road operation. In addition, a chassis dynamometer sequence, including the Federal Test Procedure, the EPA Highway Cycle, and constant speed operation, was executed for each vehicle. The fuel consumption during the warm-up period immediately following cold starting of the vehicle was also investigated.

The primary purpose of this report is a discussion of the most recent results obtained by the Southwest Research Institute in support of TSC activities. However, a broad spectrum of tasks have been pursued during the course of the program, and a brief review of the entire scope is appropriate.

The first phase of the program was initiated in mid-1973. This effort had as its goal the identification and evaluation of possible improvements to automobile fuel consumption. A number of devices and systems suitable for short term improvements in fuel economy were considered, and test data were obtained for a small fleet of standard and intermediate size vehicles typical of 1973 model year production. A draft report dealing with this phase of the program was submitted in January 1974, and the published edition of the report was issued early in 1975.

A subsequent program phase was devoted to the evaluation of techniques for fuel measurement during chassis dynamometer tests. A dynamometer procedure including urban, highway, and constant speed operation was executed with a number of vehicles representing the spectrum of available automobile sizes and manufacturers. Fuel consumption during each element of the test procedure was measured by a direct weight technique, a volumetric technique, and a carbon balance method. The results of this test sequence were reported at the previous AEEP Conference, and the formal report covering this phase of the total program is presently in the production process at TSC.

The most recent phase of the program has involved testing of subcompact vehicles in order to acquire data for use in TSC evaluations and simulations. The vehicle fleet used for this process has included a Chevrolet Vega, a Ford Pinto, a Toyota Corolla, a Volkswagen Sedan II, a Volkswagen Rabbit, and a Peugeot 504 Diesel. In addition, elements of the program have been devoted to the acquisition of tire rolling resistance data and to the performance of a series of dynamometer tests using different inertia weights and vehicle loads.

The vehicle testing program has included operation of engines alone on stationary dynamometers, road tests during which fuel consumption was measured under operating conditions, chassis dynamometer tests, and warm-up tests devoted to the determination of vehicle fuel consumption immediately following a cold start.

The engine test phase of the project was devoted to the acquisition of engine map data. The engines were removed from the vehicles and operated on stationary dynamometers over the entire speed/load range. The results of this series of tests allowed maps to be constructed according to the typical format; a preliminary example is shown in Figure 1. This display depicts lines of constant brake specific fuel consumption in terms of torque and engine speed for one of the engines involved in the program. During the dynamometer tests engine friction was also determined, as shown in Figure 2. The engines were motored under both wide-open and closed-throttle conditions, and the horsepower required for driving the engine at various speeds was measured. In addition, measurements were made of the fuel consumption during open throttle and closed throttle operation. Typical results are shown in Figure 3.

Vehicle fuel consumption during road operation was measured through the use of an instrumentation system developed for the purpose. The vehicle speed, engine speed, manifold vacuum, and fuel flow rate were recorded along with an indication of vehicle acceleration, and, for suitably equipped vehicles, measurements of the driveshaft torque and speed were obtained. The system was capable of measuring the quantities of interest during very short (0.25 second) intervals in order to remove the

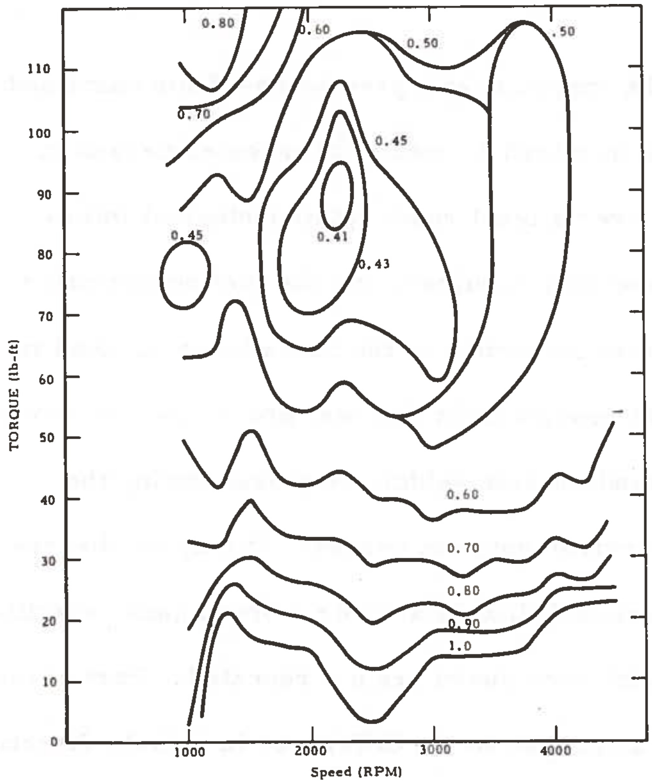

Figure 1. Engine Fuel Map

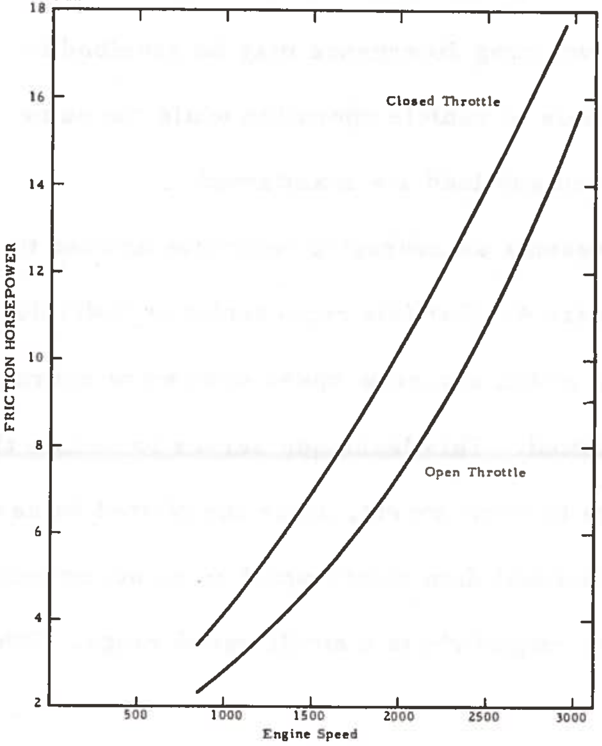

Figure 2. Engine Friction

necessity for vehicle operation at a precise speed for sustained periods. Data were acquired by means of repeated passes in opposite directions over a level road. Meteorological information was simultaneously acquired, and the fuel consumption results were corrected according to the procedures outlined in SAE J1082. Typical results from this test procedure are shown in Figure 4 for a standard size vehicle employed during the development of the instrumentation system. It may be observed that the instantaneous fuel flow data cover a broad band; specific values associated with each speed are not repeated. Part of this divergence may be attributed to the difference in vehicle direction; data points for the two directions traveled are separately identified in the figure. The remaining divergence may be ascribed to differences in the details of vehicle operation while the same nominal values of speed and load are maintained.

Figure 5 represents an averaging technique applied to the data appearing in Figure 4. For this representation individual data points occurring within a narrow speed band were averaged and the result was plotted. This technique serves to reduce the divergence in the data to some extent, since the plotted values reflect only those individual data points which were accompanied by others of a similar magnitude in a small speed range. Other

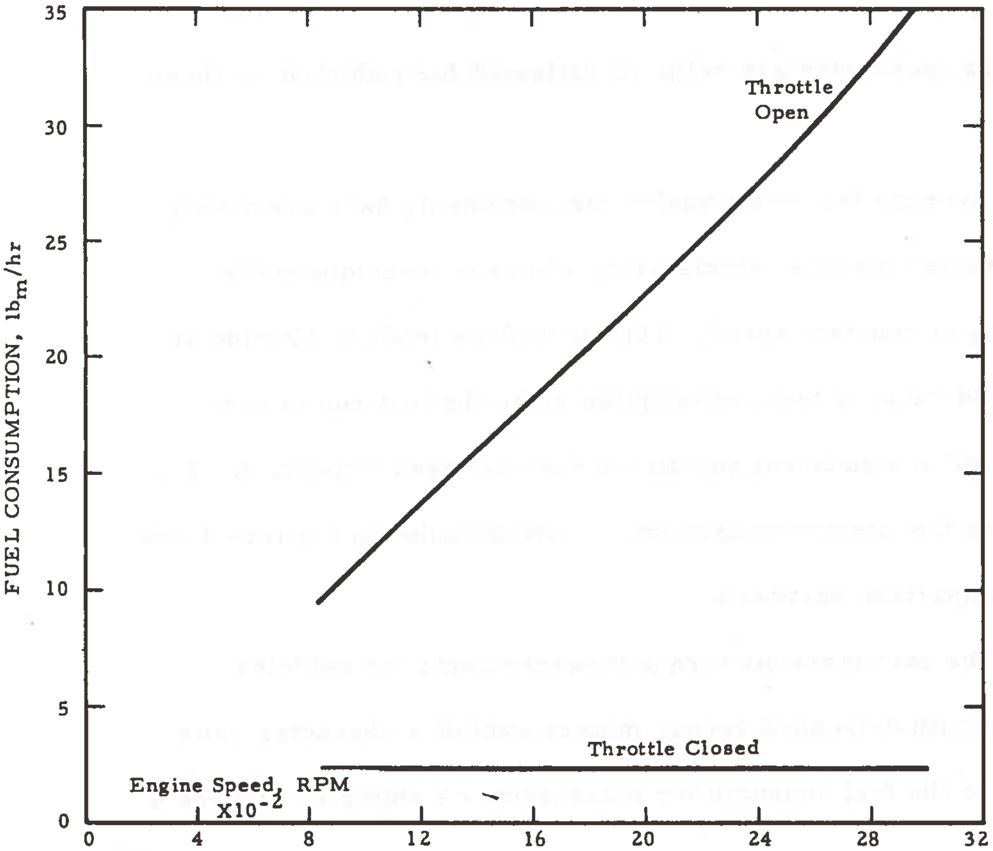

Figure 3. Engine Fuel Consumption, Motoring Conditions

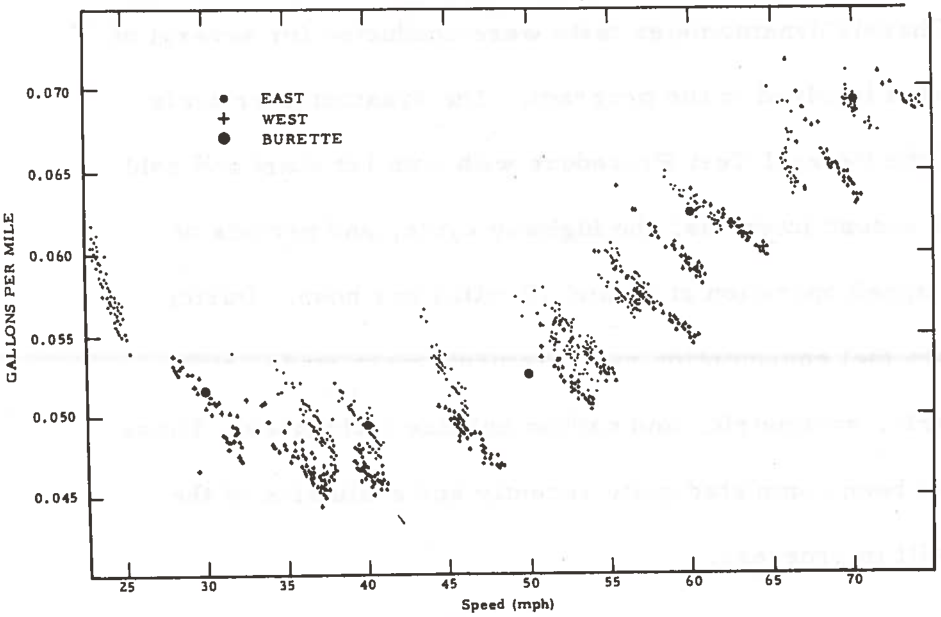

Figure 4. Road Fuel Consumption

averaging techniques are being investigated for reduction of these data.

Average fuel consumption measurements have previously been obtained for this vehicle using a burette technique while operating at constant speed. This procedure tends to provide an integrated value of fuel consumption since the test run is continued until a significant quantity of fuel has been consumed. The results of the burette measurements are included in Figures 4 and 5 for comparison purposes.

The instantaneous torque measurements for vehicles equipped with driveshaft torque meters exhibit a character quite similar to the fuel consumption measurements shown in Figures 4 and 5.

Chassis dynamometer tests were conducted for several of the vehicles involved in the program. The dynamometer cycle included the Federal Test Procedure with both hot start and cold start 505 second intervals, the highway cycle, and periods of constant speed operation at 55 and 70 miles per hour. During these tests fuel consumption measurements were made using gravimetric, volumetric, and carbon balance techniques. These tests have been completed quite recently and evaluation of the data is still in progress.

Another series of tests was conducted in order to evaluate the warm up characteristics of several of the vehicles involved in the program. During these tests vehicle operation was initiated from a cold start on the dynamometer, and a record of fuel consumption was made as a particular mode of operation was performed. Five test procedures were employed:

1. Cold start followed by idle
2. Cold start, 20 second idle, constant speed operation at 30 mph
3. Cold start, 20 second idle, constant speed operation at 55 mph
4. Cold start, 20 second idle, operation at a cyclic speed centered on 30 mph.
5. Cold start, 20 second idle, operation at a cyclic speed centered on 55 mph.

During the execution of the test procedures, measurements were made of the fuel flow rate as a function of time. Figure 6 indicates a typical record of this type. An initial high rate of fuel consumption is indicated, followed by a decreasing rate until some constant value is attained. The results of the warm up tests were phrased in terms of cumulative fuel consumption as a function of time during the test; a typical graph of

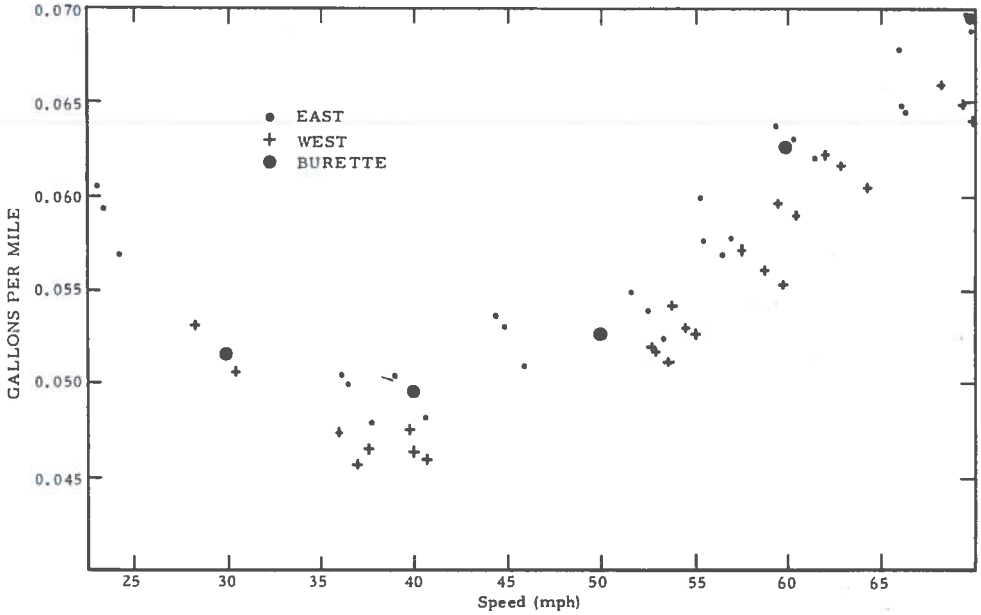

Figure 5. Road Fuel Consumption (Data Averaged in Groups)

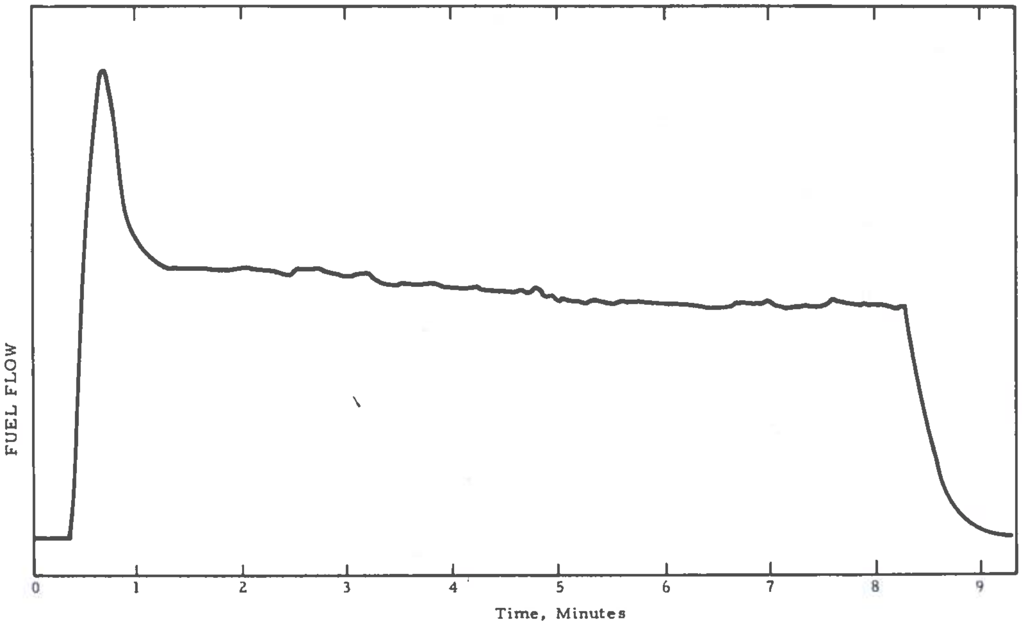

Figure 6. Warm-Up Test Data Format

this type is shown in Figure 7. In addition, the availability of a speed/time characteristic for the test routine allowed the calculation of fuel mileage as a function of distance; a typical result of this type is shown in Figure 8. Representations of this type were obtained for all tests except the continuous idle procedure.

A recently completed element of the program has involved the performance of chassis dynamometer procedures for a single vehicle at various loading conditions. The Volkswagen Rabbit was subjected to a series of tests in which the inertia weight and dynamometer load were set at different values for each run. Inertia weights from 1750 lbs to 3500 lbs were employed, along with the corresponding loads as specified in the Federal Register. Fuel consumption and emissions data were recorded during each procedure. The results of the tests are presently being evaluated; however, some preliminary data are shown in Figure 9. This representation depicts fuel economy as a function of inertia weight; the fuel economy values are normalized in terms of a single inertia weight. It may be observed that the economy values decrease as the loading on the vehicle is increased. Although numerous variables such as vehicle calibration and tire roll interaction were not evaluated during the test procedures, it is hoped that these results may provide a preliminary evaluation of the

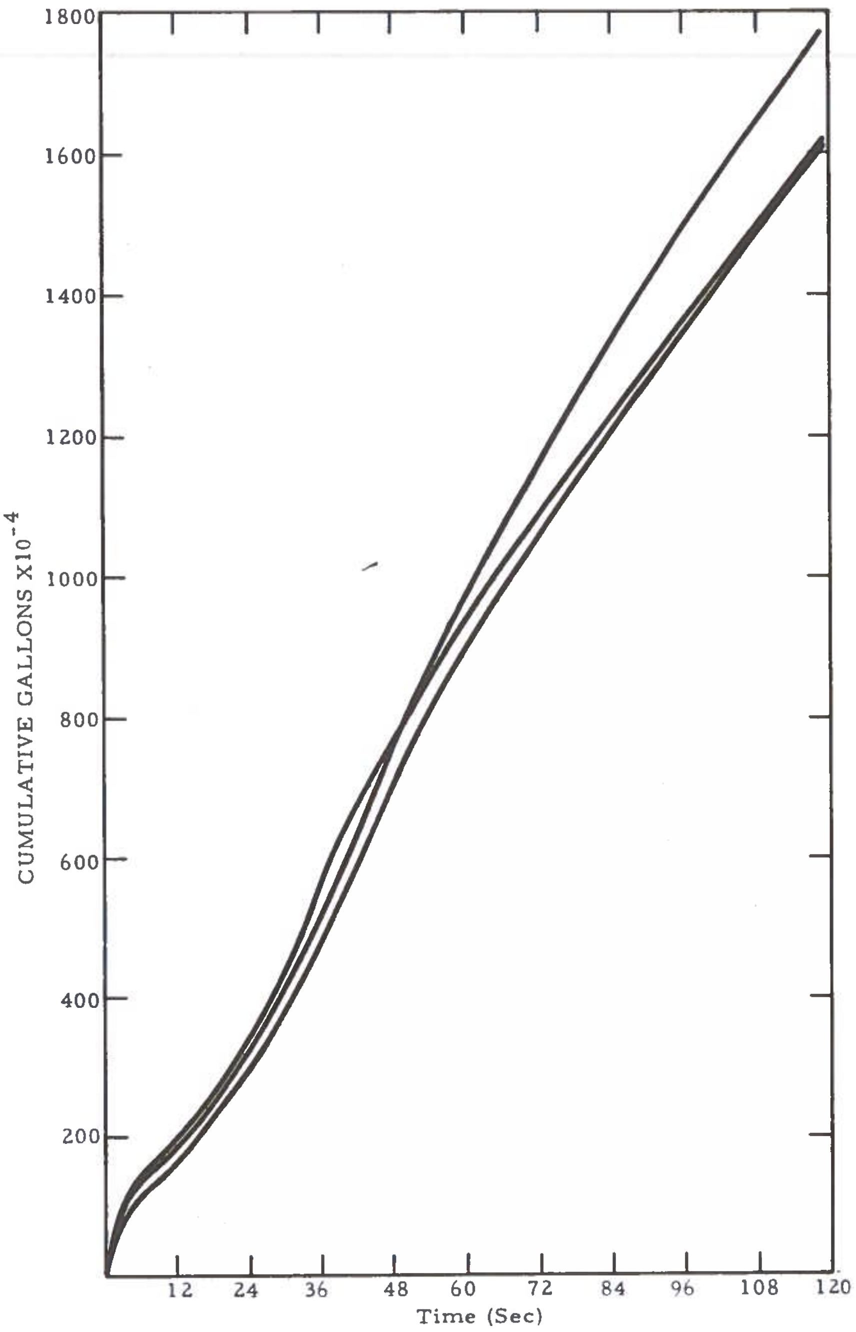

Figure 7. Cumulative Fuel Flow During Warm-Up Test

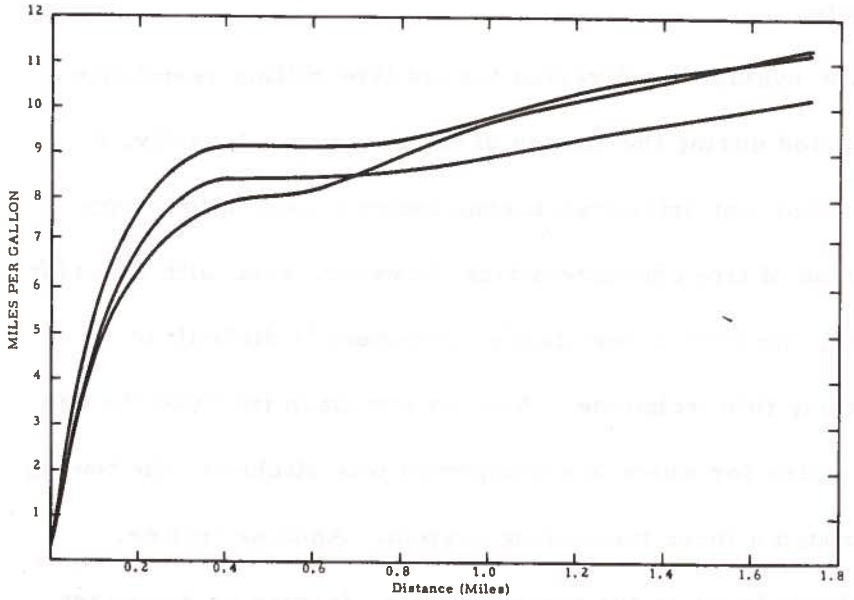

Figure 8. Mileage During Warm-Up Test

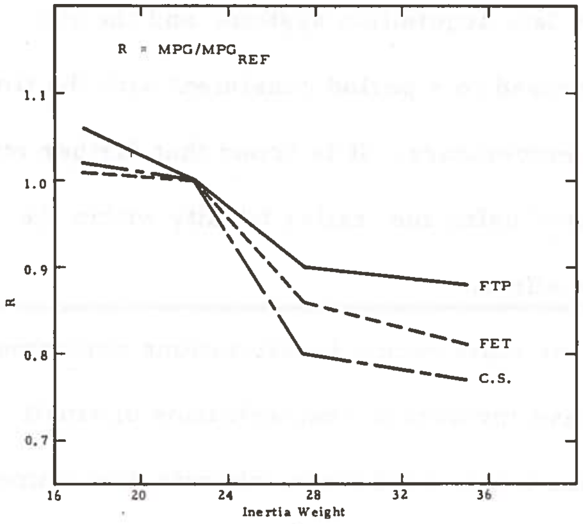

Figure 9. Relative Fuel Mileage During Variable Inertia Weight Test

effect of substituting a smaller engine for the existing engine in a large vehicle.

Some evaluations directed toward tire rolling resistance were conducted during the course of the program. Initially, it was anticipated that driveshaft torque meters would allow some interpretation of tire characteristics; however, even with superior quality data, the rolling resistance component is difficult to separate using this technique. Another approach involved the use of a dual trailer for which one component was hitched to the towing vehicle through a force measuring system. Another trailer, hitched independently to the towing vehicle, formed an enclosure about the primary trailer for the purpose of reducing the aerodynamic effect. Although some data has been acquired, it will be necessary to improve the quality of the mechanical and electrical filters used in the data acquisition system, and the run duration must be increased to a period consistent with the time constant for the tire temperature. It is hoped that further investigations can be conducted using the trailer facility within the context of the present effort.

In summary, the most recent investigations performed during the program have involved characterization of small vehicles through engine tests, road tests, chassis dynamometer tests, and warm up tests. In addition, some information has been obtained concerning tire rolling resistance and the effect of vehicle load on fuel consumption. It is expected that a draft final report will be completed shortly; copies will be available for distribution following the review and production processes.

# EVALUATION OF AUTOMOTIVE FUEL FLOWMETERS

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## ABSTRACT

A description is given of laboratory apparatus and procedures for evaluating gasoline flowmeters under conditions simulating the automotive environment. Preliminary results are reported on tests of three commercially available automotive fuel flowmeters.

The Transportation Systems Center has asked the National Bureau of Standards to evaluate several commercially available automotive fuel flowmeters under a laboratory simulation of the automotive environment. Since a rationale for this work has been presented previously,[1] the present paper will be limited to a description of the laboratory apparatus and procedure used and to a report of some of the preliminary results obtained. It should be emphasized that only selected results are reported here and that more measurements will be reported at a later date. The apparent emphasis in limiting this report to three meters is an unintended result of reporting results midway in the test program. It should also be emphasized that only one meter of each kind was tested and that the present results may not reliably indicate how other meters made by the same manufacturer will perform.

## 1. APPARATUS AND PROCEDURE

A schematic of the flow system is shown in Fig. 1. Since the pressure regulator maintains a constant pressure upstream of the meter, the flowrate is held constant for any given setting of the flow adjusting valve.

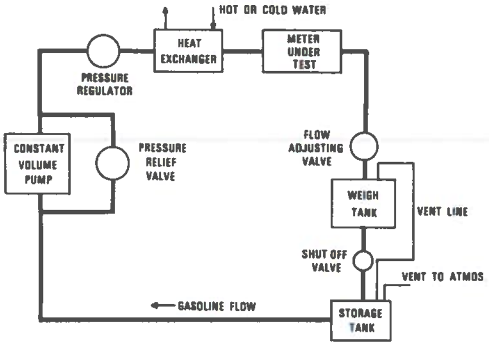


Fig 1. Calibration Setup

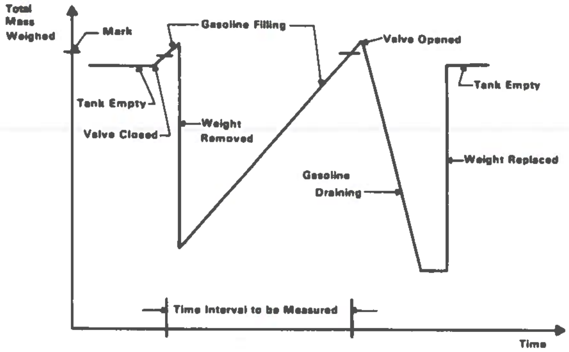


Fig 2. Substitution Weighing System

The substitution weighing procedure graphed in Fig 2 was used to eliminate some possible errors. The weigh tank is attached to a pan on one side of an equal arm balance. At the start of a measurement a (substitution) weight of known mass is placed on the pan. Sufficient tare weight is on the pan on the other side of the balance to tilt the second pan down. With the gasoline flowing through the system in a steady state, the shut-off valve is closed so that the tank will fill. When sufficient gasoline is collected to swing the balance arm, it interrupts a light beam, which starts a timer. Then the substitution weight is removed, and the arm swings back. When sufficient additional gasoline is collected to swing the balance arm again, it again interrupts the light beam, which stops the timer. Finally, the shut-off valve is opened draining the tank, and the substitution weight is replaced. The average flowrate is the substituted mass divided by the collection time interval.

A significant source of error is shown in Fig 3. The mass of liquid in the column is not negligible. Also there is another significant source of error: The force exerted on the liquid in the tank by the liquid jet is larger at the initial level than at the final level due to the acceleration of the jet by gravity. Fortunately the difference between the initial and final force is exactly equal to the weight of the liquid in the column, and so the two errors cancel exactly.

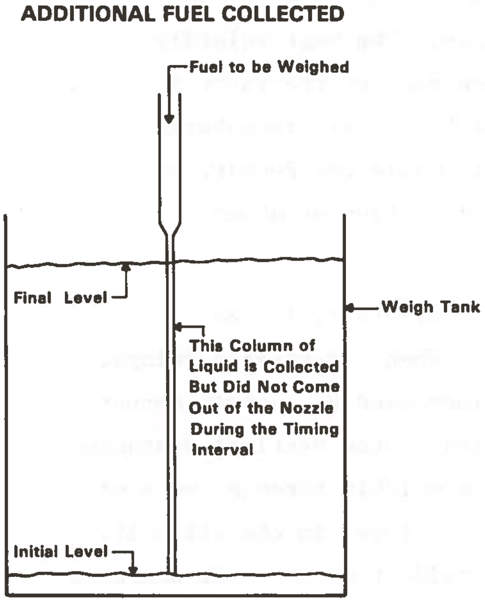


Fig 3. Source of Error

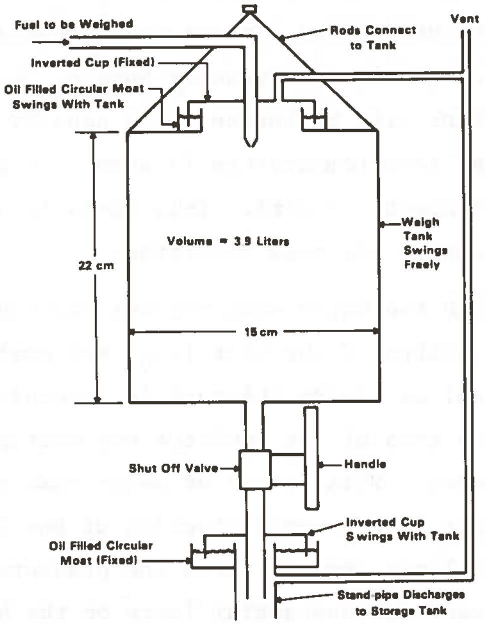


Figure 4. Weigh Tank and Vapor Seals

The weigh tank is equipped with an oil moat as a vapor seal (Fig 4) to minimumize the excape of vapor during the measurement. Of course a volume of vapor equal to the volume of liquid collected will go through the vent line to the storage tank during weigh tank filling. However, no vapor will be forced out of the vent to the atmosphere by the filling because the net volume of liquid in the entire system is constant. Similarly no air will be drawn in through the vent from the atmosphere when the shut-off valve is opened. As a result, after a while the weigh tank will contain only vapor instead of air, and further vaporization of the gasoline will be reduced somewhat. So the mass of vapor lost during a weighing period should be small.

The mass of vapor displaced by the rising liquid in the weigh tank, on the other hand, is not quite negligible. The most volatile component of gasoline is usually butane. Hence much of the vapor in the weigh tank will be butane. The density of butane at atmospheric pressure and room temperature is about 2.6 g/l, while the density of gasoline is about .73 g/ml. This leads to a correction of about + .36 percent to the mass collected.

Although the vapor seal reduces one source of error, it can introduce another if the vent lines are small. When the balance swings, the vapor volume inside the tank is suddenly increased by a small amount equal to the area of the inverted cup multiplied by the vertical distance the tank moves. This volume of vapor must pass quickly through the vent line in order to prevent distortion of the liquid level in the oil moat. If the vent lines are not large the pressure inside the tank will decrease enough to cause a substantial force on the balance. At the lower seal a similar effect occurs but in the opposite direction. Unfortunately the forces do not cancel because they depend upon the vapor volume in each closed region, and these are not equal. For the same reason the effect is different when the tank is full and when it is empty. With the vent lines used at first this caused a small difference in the response time of the balance arm at the upper and lower fill marks. To minimize this effect the vent lines were increased from 4 mm to 7 mm inside diameter. The resulting response is seen in Fig 5 to be sufficiently similar at the two marks to result in a negligible error since the shortest collection time was 50 seconds.

The precision of the flowrate calibration can be estimated as follows. The sensitivity of the balance is better than 0.1 gram, and the smallest mass collected was 200 grams (for the three lowest flowrates). This gives a readibility of .05 percent for each calibration.

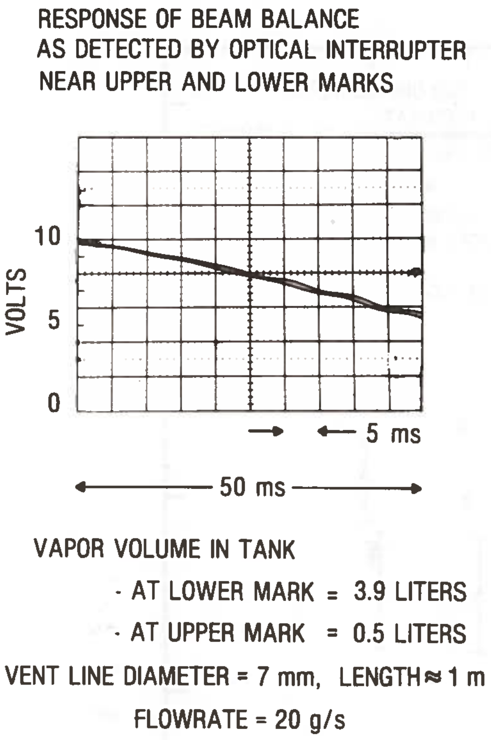


Fig 5. Error Evaluation

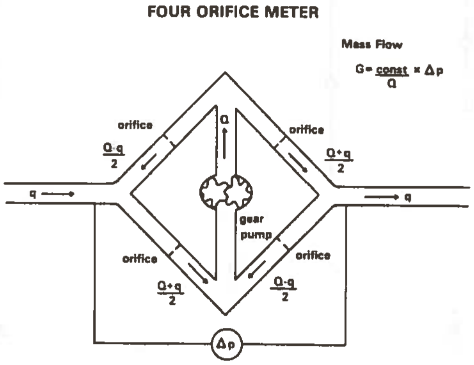


Fig 6. Transfer Standard

## 2. TRANSFER STANDARD METER

The first meter calibrated is shown schematically in Fig 6. The particular meter tested gave an 11.5 percent error when first calibrated because its voltage output had too high an impedance for the 100 kΩ input impedance of a typical voltage-to-frequency converter. So the electronic circuit was redesigned, and the meter span and linearity were adjusted. The calibration curve for the modified meter is shown in Fig 7. Each data point is the average of five collections, and the vertical bar shows plus and minus one standard deviation obtained from these five collections. No correction was made for the mass of vapor displaced by the liquid collected.

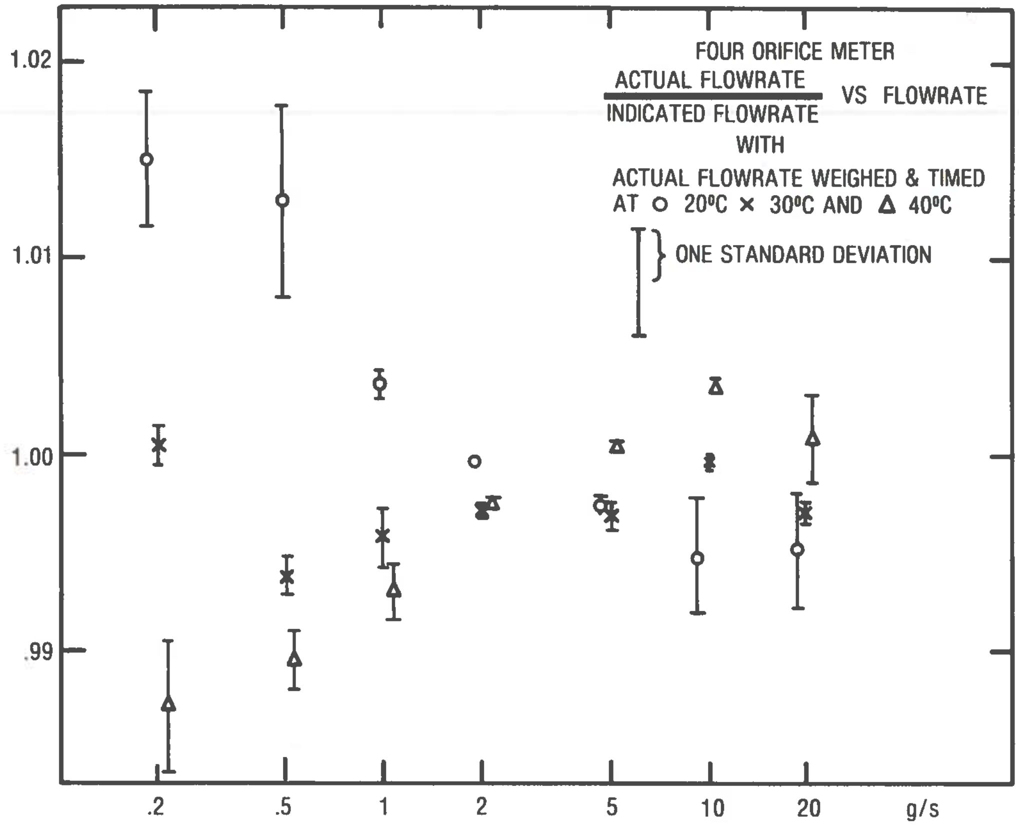


Fig 7. Transfer Standard Meter Calibration

Even though this meter is not perfect, it is useful as a transfer standard for testing other meters because it gives one pulse for each milligram of gasoline passing through it. It is used as shown in Fig 8. The weigh tank is left in the flow loop for convenience in calibrating. It is not used for other tests except to confirm results. The other tests are performed using the circuit of Fig 9 in order to plot the meter factor (actual flowrate/indicated flowrate) on the Y axis of the X-Y recorder. The counter displays the ratio of flowrates, and the digital to analog converter converts a selected three digits of that ratio into a voltage, which is connected to the Y axis. A voltage proportional to the quantity varied (or its logarithm) is connected to the X axis.

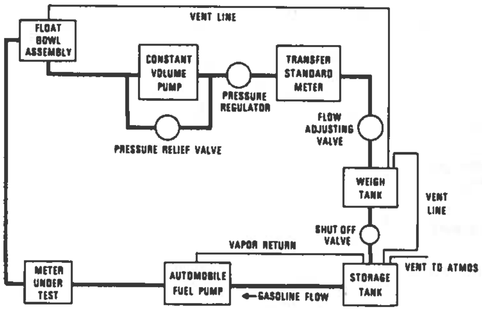


Figure 8. Flowmeter Test Setup

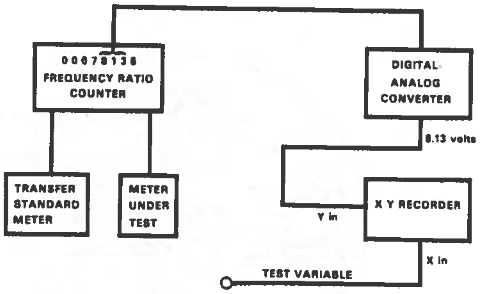


Fig 9. Wiring Schematic

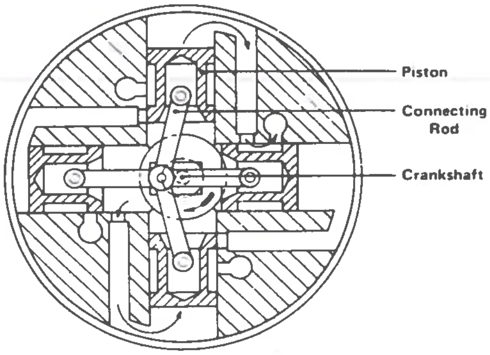
Possible X inputs with apparatus presently in our laboratory are:

Frequency of Horizontal or Vertical Vibration, 1 to 5000 Hz
Peak Vibratory Acceleration of Flowmeter or Float Bowl, 0 to
  10 x 908 cm/s$^2$
Automobile Fuel Pump Speed, 200 to 1800 pulses per minute
DC Supply Voltage, 8-16 volts
Amplitude of 60 Hz Voltage Superposed on Supply
Flowrate, 0.2 to 20 g/s
Temperature, 0 to 65°C
  of fuel at meter input
  of flowmeter
  of fuel at float bowl

Unfortunately the fuel temperature and the flowrate can not be set independently. Not all of these tests have been carried out yet, and only some of the ones that have are reported in the following.

## 3. FOUR PISTON METER

This type of meter is shown in Fig 10, and its calibration curve in Fig 11. Each point is the average of five collections, and the bar is one standard deviation. A measurement of the gasoline density was made, and tables of the temperature dependence of the density were used in order to convert the indicated volume into mass. These tables make



Sectional View Showing
Internal Mechanism

Fig 10. Four Piston Meter

a correction for air displaced by the rising liquid in the weigh tank. Since air has a density of about 1.2 g/l, this correction was only about half as big as necessary for the butane actually displaced so a further correction of about + .19 percent should be made. The mass collected was 200 g for the three lowest flowrates, 500 g for the next two, and 1 kg for the highest two. The indicated flowrate was obtained from a visual readout, which gives total flow in 1 ml increments and total time in 1 s increments.

The displayed total flow increases by 1 ml for each pulse from the metering element except that occasionally the display increases by 2 ml. For the particular meter tested, the display always skips the values shown in the following table.

| Display Values (ml) Skipped | | | | Differences |
|---|---|---|---|---|
| 15 | 122 | 229 | 366 | 15 |
| 30 | 137 | 244 | 351 | 15 |
| 45 | 152 | 259 | 366 | 15 |
| 61 | 168 | 275 | 382 | 15 |
| 76 | 183 | 290 | 387 | 15 |
| 91 | 198 | 305 | 412 | 15 |
| 106 | 213 | 320 | 427 | 16 |
| | | | | 107 |

It is apparent that the pattern repeats every 107 ml and so the table has not been continued past 427 ml. It follows that on the average the calibration of this meter is approximately 1.07 ml per pulse from the metering element. One can also see that due to the occasional skipping the displayed total flow can be too small by as much as .99 liter.

In addition there is another noncumulative error that occurs with this meter. The meter calibration differs slightly from pulse to pulse because there are 10 pulses per revolution of the crank. The volumes for the first five pulses are 1.10 ml, 1.10 ml, 0.91 ml, 1.09 ml, and 1.16 ml, and the second five pulses repeat this pattern. Thus, one time out of five, as much as 1.15 ml can flow before the next pulse comes. The sum of these two errors can make the total flow displayed by this meter too small by as much as 0.99 ml + 1.15 ml = 2.14 ml even if the metering element were perfectly accurate. This contributed to the scatter in Fig 11.

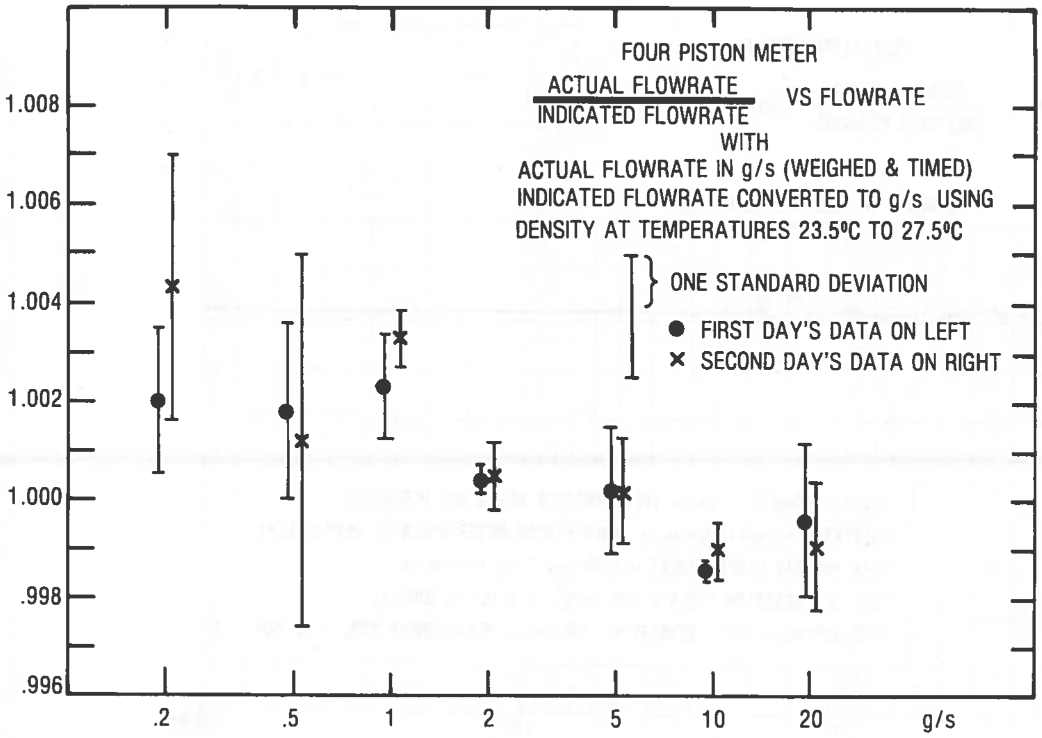


Fig 11. Four Piston Meter Calibration Curve

Note that another metering element made by the same manufacturer could have a calibration less accurate than this one. It could be off as much as 1/2 percent because the volume per pulse could be as large as 1.075 ml and the nominal calibration would still be 1.07 ml. Only if the volume per pulse were larger than 1.075 ml would the nominal calibration of the readout be changed to 1.08 ml. The particular meter tested may have been selected by the manufacturer because it did not have an error this large.

The meter evaluated has no pulse output for use in the other tests described previously. So its cover was removed, and pulses were taken from a convenient point at the input of the readout circuit. Some results of vibrating this meter and using the technique described in the previous section are shown in Figs 12-15, which show an error near 16 Hz. The factor 1.07 appears in the ordinate because the meter gives a pulse for each 1.07 ml. The meter factor is averaged over a multiple of 10 pulses in order to smooth out the differences in the volume per pulse described previously. The last graph shows an immense error at low flowrates.

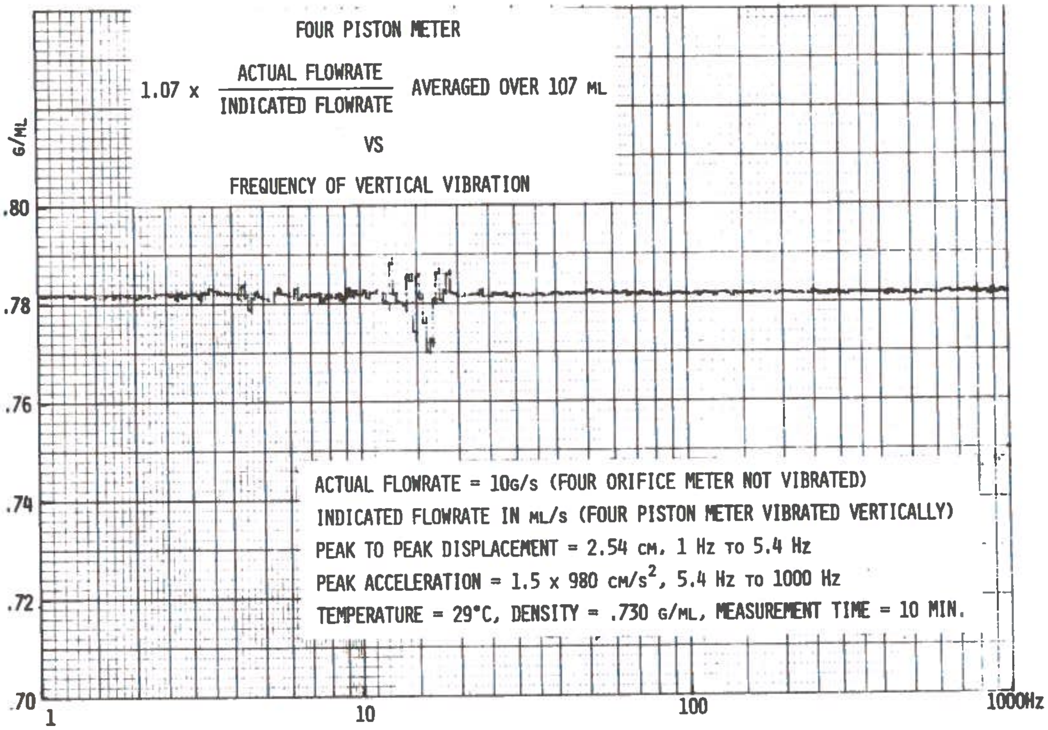


Fig 12. Vibration Test of Four Piston Meter - Vs. Frequency of Vertical Vibration (107 ML)

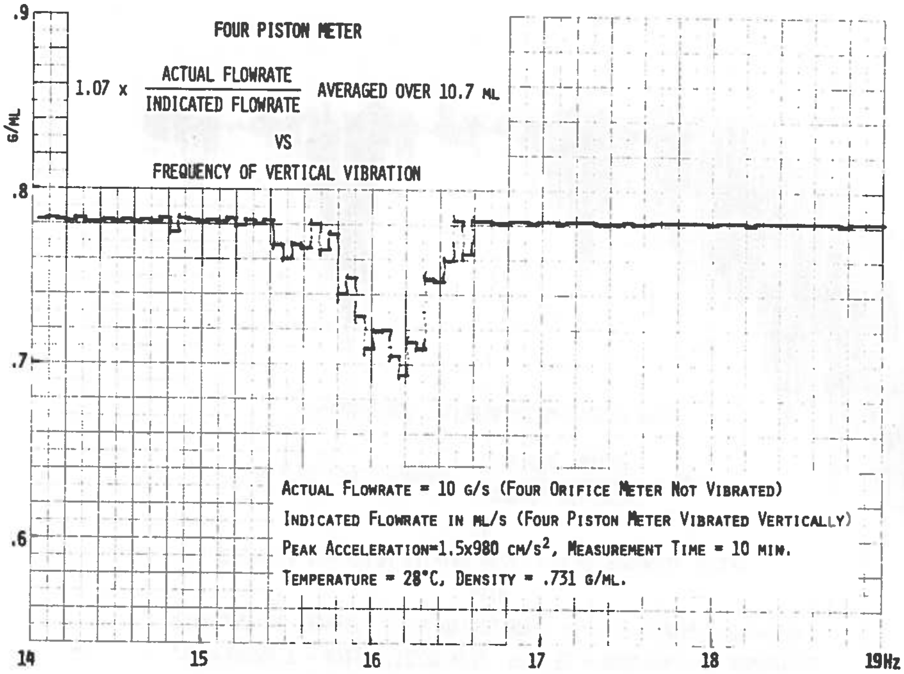


Fig. 13. Vibration Test of Four Piston Meter Vs. Frequency of Vertical Vibration (10.7 ML)

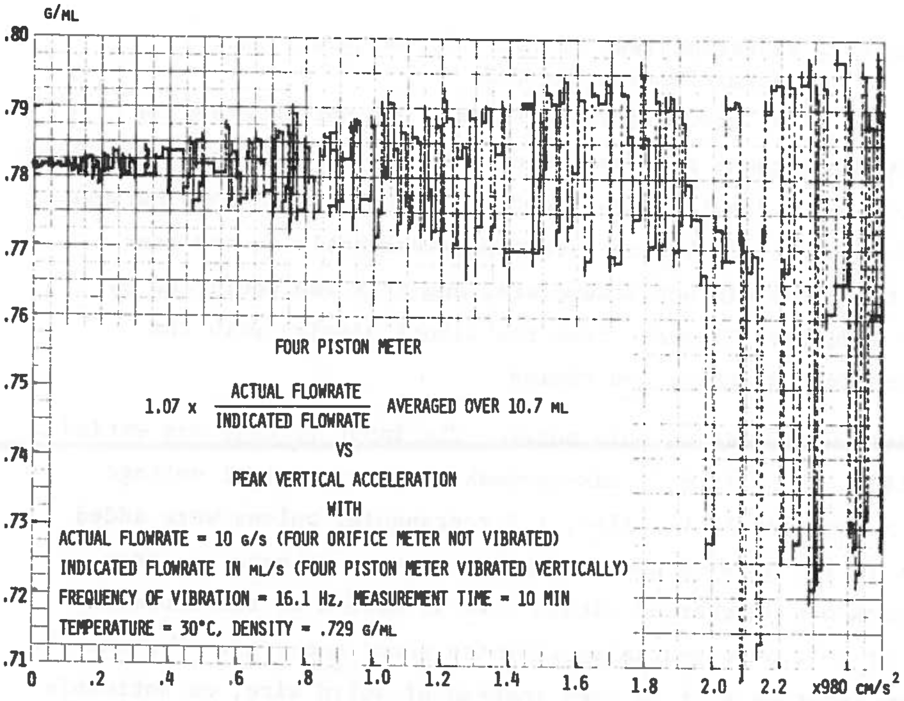


Fig 14. Vibration Test of Four Piston Meter Vs. Peak Vertical Acceleration

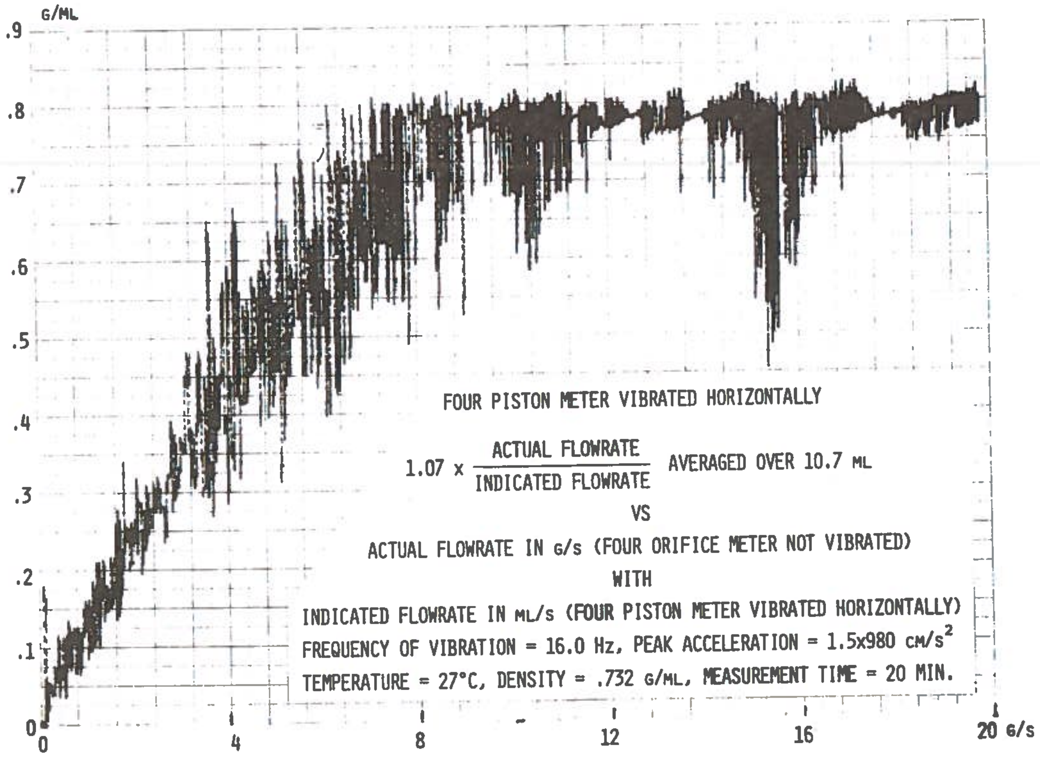


Fig 15. Vibration Test of Four Piston Meter Vs. Actual Flowrate in G/S

However, the error shown in these figures was not observed on the visual display because the readout electronics incorporated an up-down counter. The display was observed to count up and down between adjacent values many times before advancing permanently to the next value. Thus the error did not accumulate, and this was confirmed by comparing the indicated flowrate from the visual display with the actual flowrate from weighing and timing.

Other tests were made on this meter. The input voltage was varied from 8 V to 16 V. An 8 V peak-to-peak 60 Hz sinusoidal voltage was added to a constant 12 V. Also, 1 V rectangular pulses were added to a constant 12 V. None of these caused the meter to make an error. But when a spark was discharged within several meters of the flowmeter (with its cover on), an essentially infinite error occurred. Fortunately, when resistive ignition wire is used instead of solid wire, no noticable error occurred.

If time permits, further tests will be performed on this meter in the future.

### 4. POSITIVE DISPLACEMENT PUMP METER

The last meter tested has a single piston with a rigid connecting rod coupled to the shaft of an electric motor at a slight angle. The coupling involves a pin travelling in a groove so that the piston oscillates as the motor shaft turns. The meter has an output of 12,000 pulses per gallon. The calibration curve for this meter is shown in Fig 16. Again each point is the average of five collections, and the bar is one standard deviation. Density was measured and tables[2] were used to convert the indicated volume into mass. Again a correction of about + .19 percent should be made.

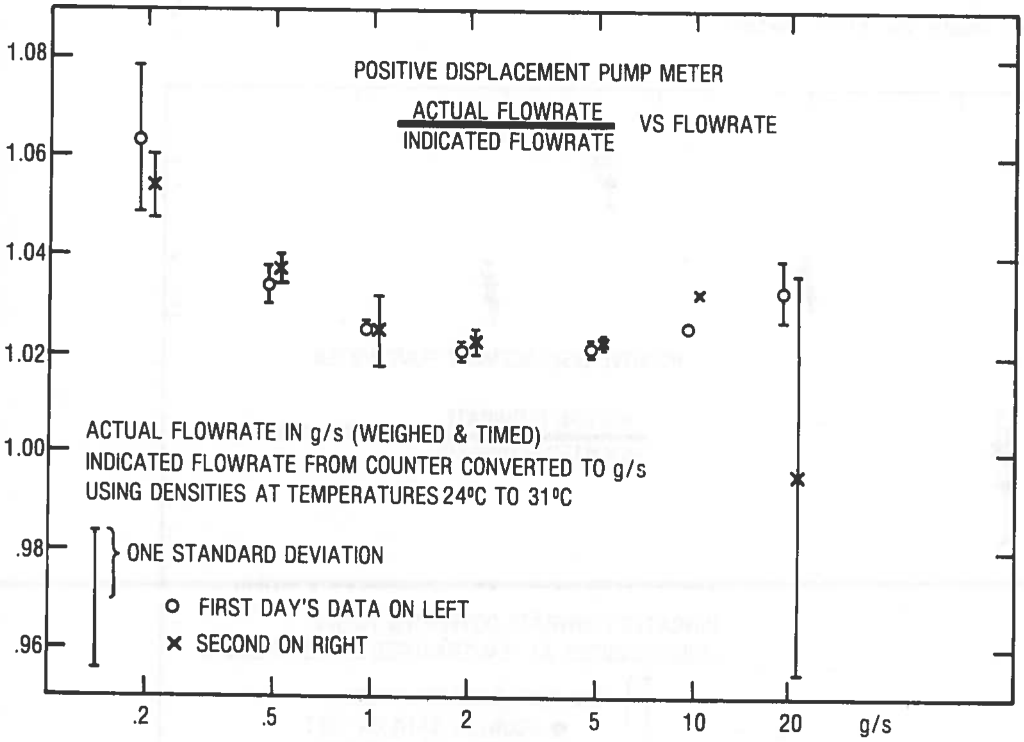


Fig 16. Calibration Curve

The collections that gave rise to the large bar at 20 g/s were taken at the beginning of the second day. The first two collections agreed with the previous day's collections. The last three at that flowrate gave much higher indications. No cause for this could be found. All subsequent collections that day agreed with the previous collections. However, collections taken on subsequent days that were too late to be included in the graph were occasionally also erratic. These erratic collections occurred at other flow rates as well. The cause for the erratic readings has not been determined. The effect of supply voltage on this meter is shown in Fig 17.

Vibration and other tests on this meter were difficult to analyze because of the erratic output shown in Figs 18 and 19. This erratic output seemed to occur at all times and appears to be unrelated to that shown in Fig 16. Because of the erratic behavior, no further tests were made on this meter.

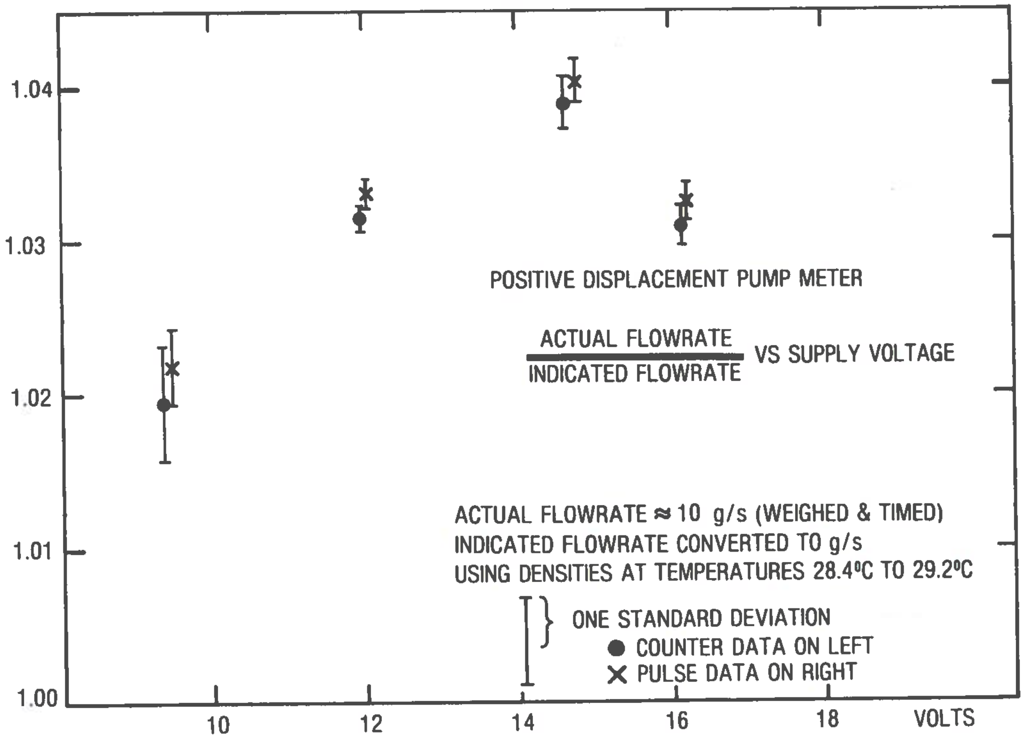


Fig 17. Supply Voltage Dependence

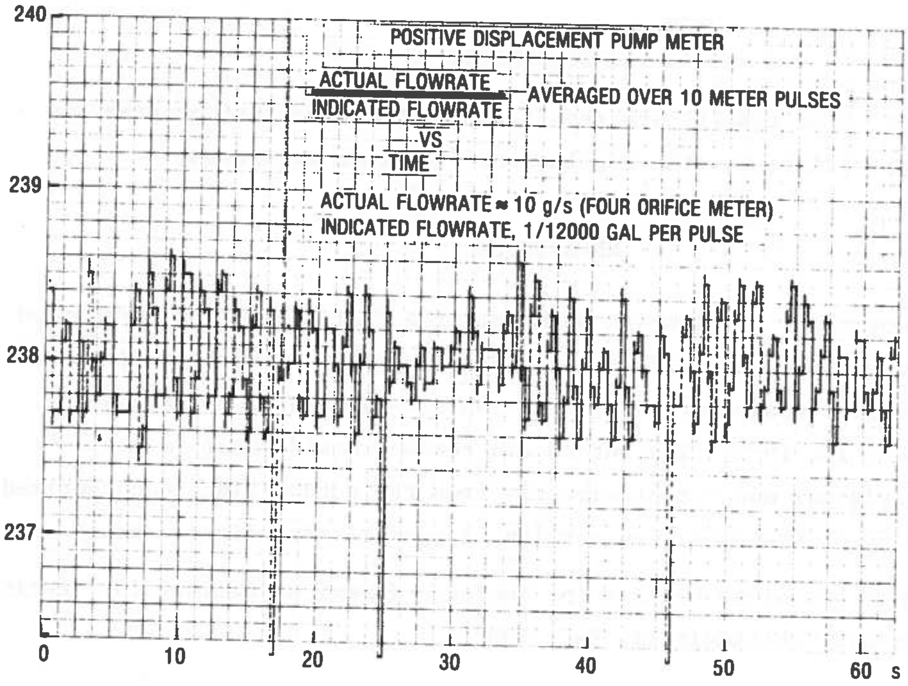


Fig. 18. Erratic Output Averaged Over 10 Meter Passes

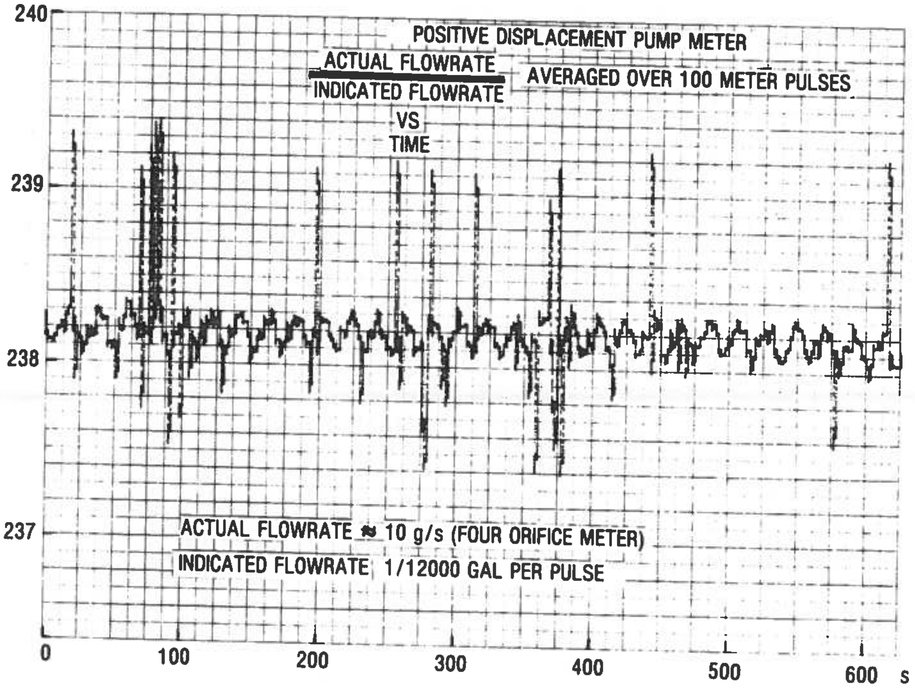


Fig. 19. Output Averaged Over 100 Meter Passes

## 5. DISCUSSION

Since these results are reported midway in the test program, it is not appropriate to draw conclusions from them at present.

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2. ASTM-IP Petroleum Measurement Tables. (American Society for Testing Materials, Philadelphia, Pa., 1952)

# A STUDY OF ALTERNATIVE ROLES OF THE AUTOMOBILE

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## ABSTRACT

The basic objective of this research is to formulate, analyze, and evaluate alternative policies directed toward changing the use patterns, ownership characteristics, and the technology of automotive transportation. The central focus of the research is a systematic development of alternative policy scenarios. Each scenario will be given comprehensive technical and institutional analysis with respect to various end-state impacts and transitional requirements for phased implementation. Each policy will be studied in terms of key performance characteristics, including: travel congestion, accident risk, energy consumption, air and noise pollution, and the social equity of use, ownership, and social costs. Additional impacts generated by alternative remedial policies also will be analyzed (e.g., economic and social impacts upon industry, labor, and the national economy).

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# INTRODUCTION

The Program in Environmental Systems Engineering at the University of Pittsburgh recently was awarded a contract by the Department of Transportation's Office of University Research to conduct a policy analysis of alternative roles of the automobile. Although this effort is not formally tied to the Department's Automotive Energy Efficiency Program (AEEP), we are attending this meeting to enhance coordination of our research with the various initiatives being sponsored under AEEP auspices. Since our study remains in a formative stage as of this report, our role here is more to listen rather than to relate unique progress. We appreciate this opportunity to become more familiar with the advances discussed here by AEEP contractors as well as internal TSC staff, and can reciprocate most properly now by being brief.

## THE PROBLEM

Together with other participants at this meeting, we share an interest in solving the problem of developing policies to alleviate apparent shortcomings of contemporary automotive transport, subject to a variety of technological and institutional constraints. The particular shortcomings of immediate concern include not only fuel consumption and air pollution, but also traffic congestion, accident risk, and noise pollution. We share the AEEP's concern with technological performance tradeoffs between fuel economy, air quality, safety and user costs and the penalties each of these objectives might incur within the context of standing and pending Federal legislation. Certainly it is clear from the reports heard here that these technological questions have been receiving substantial attention recently; indeed, such questions form the main thrust of AEEP.

More modest attention has been given to broader impacts of alternative policies beyond attributes of system performance *per se*. Some prior and continuing research efforts have studied the adaptive capability of the motor vehicle manufacturing industry to adjust its output, in terms of production technology and capital resources, to accommodate selective policies regarding vehicular technology. Less consideration has been given to the analysis of more indirect national effects, such as the economic ramifications upon output and employment levels through inter-industry relationships, fiscal impacts of various policies upon governmental agencies responsible for highway construction and maintenance, and social impacts in terms of distributional aspects of user costs and conceivable challenges to traditional life styles. One objective of our study is to bring such indirect effects into the policy-analytic calculus.

Moreover, even if technical analyses of performance and other impacts offer strong support for a candidate policy, there remain some rather delicate concerns regarding how that policy might be implemented through the political process. These concerns involve not only the resolution of conflict among adversary interests, but also the proper concatenation of long-term policy as perhaps a series of individually more palatable actions. For these purposes it becomes necessary to characterize not only the array of automobile-related interests in society, but also to analyze the prevailing network for political "transactions" as conditioned by legal and bureaucratic processes and both governmental and corporate decision-making behavior. Our study includes analysis of such transitional mechanisms.

# ALTERNATIVE POLICY STRATEGIES

Literally hundreds of suggestions have been advanced within the scientific and journalistic communities for alleviating the apparent shortcomings of automotive transport. Merely to classify these candidate courses of action in terms of a "clean" taxonomy is a challenging undertaking; such taxonomical development, indeed, is one of the current concerns in our research effort. For purposes of clarifying the scope of our work, however, it is useful to consider here two policy dimensions, namely, "implementation focus" and "temporal horizon".

Implementation focus is defined to distinguish between four broad categories of policy, i.e., actions whose immediate manifestations are in the technology, the patterns of ownership, the patterns of use, or the industrial organization (manufacturing and marketing) of automotive transport. Temporal horizon here refers simply to the short term versus long-term distinction. Prior technical studies have focused on short-term use controls for air quality enhancement [EPA, 1973], short- and long-term changes in the economic organization of vehicle manufacturing and retailing [White, 1971] and, of course, short- and long-term changes in vehicle technology. DOT and EPA [1974] jointly have examined candidate fuel economy technologies mainly for delivery by 1980, and the AEEP efforts are extending that initiative to post-1980 technology.

The econometrics literature includes a variety of studies of automobile demand [e.g., Chow, 1957; Smith, 1975] which are descriptive of consumer behavior although not explicitly concerned with ownership-related policy. Also, the individual motor vehicle manufacturers have studied most of these problem areas but public documentation of such efforts is limited for obvious reasons.

Another mission of the Pitt research effort is to complement the aforementioned progress by considering long-term, non-technological policies as well as the more promising long-term changes in vehicle technology. Such candidate policies might include taxation schemes, alternative modes of nearly-personal transport, the phased redistribution of fleet composition (perhaps via supra-market interventoral means), alternative financing and retailing mechanisms, or outright vehicle standardization. Though strictly a suggestive illustration at this early stage, the following list exemplifies the range of scenarios which might be tendered for substantive policy analysis:

> Do-Nothing. Project the performance characteristics and distributional patterns of future automobile transportation if no further intervention were applied, reflecting likely economic and demographic trends as they affect automobile ownership and use

> Short-Term (VMT) Use Controls. Study the impacts and feasibility of policies directed to controls upon total vehicle-miles of travel under current ownership structures and vehicle technology, such as those controls currently being promulgated by EPA.

Composite Taxation. Study the impacts and feasibility of a mixed taxation structure which would include: modifications to existing sales/excise taxes; graduated registration fees (in terms of vehicle size, horsepower, weight and age); and user taxes (fuel taxes, congestion/access tolls, and/or parking surcharges).

Segregated Fleets. Study the impacts and feasibility of policies requiring vehicular segregation by function (e.g., intracity vs. intercity), where at least some subset of all vehicles shall comply with specified emissions, noise, size, weight and other characteristics (electric or battery-powered vehicles might be an outgrowth of this scenario, but small conventional-engine vehicles also should be considered, particularly for the short-run).

Vehicle Performance Standardization. Study the impacts and feasibility of policies (including incentives) designed to encourage the development of a low-cost 4 to 6 passenger vehicle with high fuel economy and low emission levels. The vehicle should be suitable for urban and non-urban use, and it should include other performance characteristics comparable to existing automobiles.

Expansion of Demand-Responsive Services. Study the impacts and feasibility of policies which increase the availability of taxis and dial-a-ride/minibus operations; policies could include, e.g., provisions for free entry of taxis and dial-a-ride systems and could encourage self-driving rules of operation (with either private or public fleet ownership).

Alternative Financing Arrangements. Study the impacts and feasibility of policies (including incentives) which encourage changes in historical patterns of transportation financing. Consider, e.g., changes in urban financing which enable private businesses and/or public agencies to internalize at least a portion of the social benefits resulting from improved transportation (also, this scenario might consider the possible leasing or outright free provision of transportation units as an alternative to traditional retailing mechanisms, e.g., whereby customers would contract for a vehicle plus maintenance and replacement).

> Automobile Transportation Utilities. Study the impacts and feasibility of policies directed toward long-term reorganization of economic institutions along the lines of existing telephone companies. This scenario would involve a high degree of technical standardization and modular compatibility which would permit individuals to "plug in" to an (electronic or other) guideway and/or chassis system at various locations.

Clearly it would be overzealous to attempt to study many such policies in great depth. Although we hope to build upon those methods of technical analysis discussed here by other participants (e.g., models of automobile ownership, fleet replacement, and VMT trends), the more creative pursuits in our work involve the analysis of indirect impacts and transitional requirements. By integrating available technical data with these broader analyses, we hope to develop a paradigm for making consistent evaluative comparisons between such diverse policy strategies.

## WORK PLAN

As indicated earlier, the basic mission of our research is to develop policy strategies for mitigating the shortcomings of automotive transport, as they might develop into the future under "Null" circumstances. Like much of planning and problem-solving generally, we shall compose alternative policies, analyze their impacts, and offer comparative evaluation of the alternatives on the basis of such impact estimates. However, two features of our approach distinguish it as complementary to recent studies.

First, although our immediate concern in fashioning alternative policies is with mitigating the projected shortcomings of automobile transport as listed earlier, we also must be cognizant of the fact that proposed policies will generate additional impacts of importance. For example, a proposal for standardized small cars may affect significantly the economic fortunes of the motor-vehicle manufacturing sector, its related industries, employment levels therein and, indeed, the entire national economy. As another example, proposals to reduce vehicle-miles of automobile travel (VMT) under contemporary fuel-tax structures may reduce substantially the revenue stream to highway agencies for road construction and maintenance, which in turn would imply similar "ripple" effects among related industries (e.g., the materials and construction sectors). Our analysis must give balanced consideration to the effects of automobile transport that we directly seek to mitigate and to these additional impacts which alternative policies might generate -- call them, respectively, "performance" and "indirect" impacts for now.

Secondly, we explicitly recognize that many problems of implementation may be encountered beyond sheer decision-making based on "end-state" impact tradeoffs. These problems may be technological, economic, social, legal or political. For example, the widespread standardization of small cars might involve delicate technological problems of fleet transition ranging from the capacity of motor-vehicle manufacturers (and their suppliers) to realign production processes to the ability of local governments to rearrange their delineation of parking spaces. This policy might also involve economic problems such as the availability of capital to support major changes in vehicle manufacture, and social problems such as the distribution of cost burdens and the adaptability of the American public to lifestyle changes implied by a loss of status differentiation.

This policy also might require resolution of legal issues such as enforcement of horsepower limitations, clarification of vehicle property rights, potential infringements upon individual mobility, and rules of trade in merchandising and maintenance of private/public fleet. It might involve political questions (beyond the obvious value conflicts over end-state impacts) such as a redefinition of jurisdictional responsibilities among government agencies. All of these problems refer to processes bearing upon the transition from the status quo to any fully implemented policy, and usually involve an analysis of institutional capacity and/or a prescription of modified institutional mechanisms to absorb/support such transition. These "transitional requirements" are a central concern of our analysis together with "end-state impacts."

Accordingly, the work plan of our research effort centers on the formulation, analysis and evaluation of alternative policies with respect to both end-state impacts and transitional requirements (see Figure 1). Alternative policies shall be specified as influences upon the use, ownership and/or technology of automotive transport, and will be fashioned from a perspective of reducing the performance effects of such transport. The end-state impact anaysis will study the likely levels of these performance impacts together with the indirect impacts of each policy alternative. The "transitional requirements analysis" will study the (technological, economic, social, legal and political) capacity of institutional structures and mechanisms to absorb the changes implied by each policy alternative, and will identify institutional modifications necessary to support or deliver such changes (including, as necessary, sequences of incremental policies). In general, these delivery considerations may depend on the character and intensity of end-state impacts; hence the horizontal arrow in Figure 1. The "comparative evaluation" endeavor purports to issue recommendations of particular policy alternatives on the basis of all end-state impacts and transitional requirements.

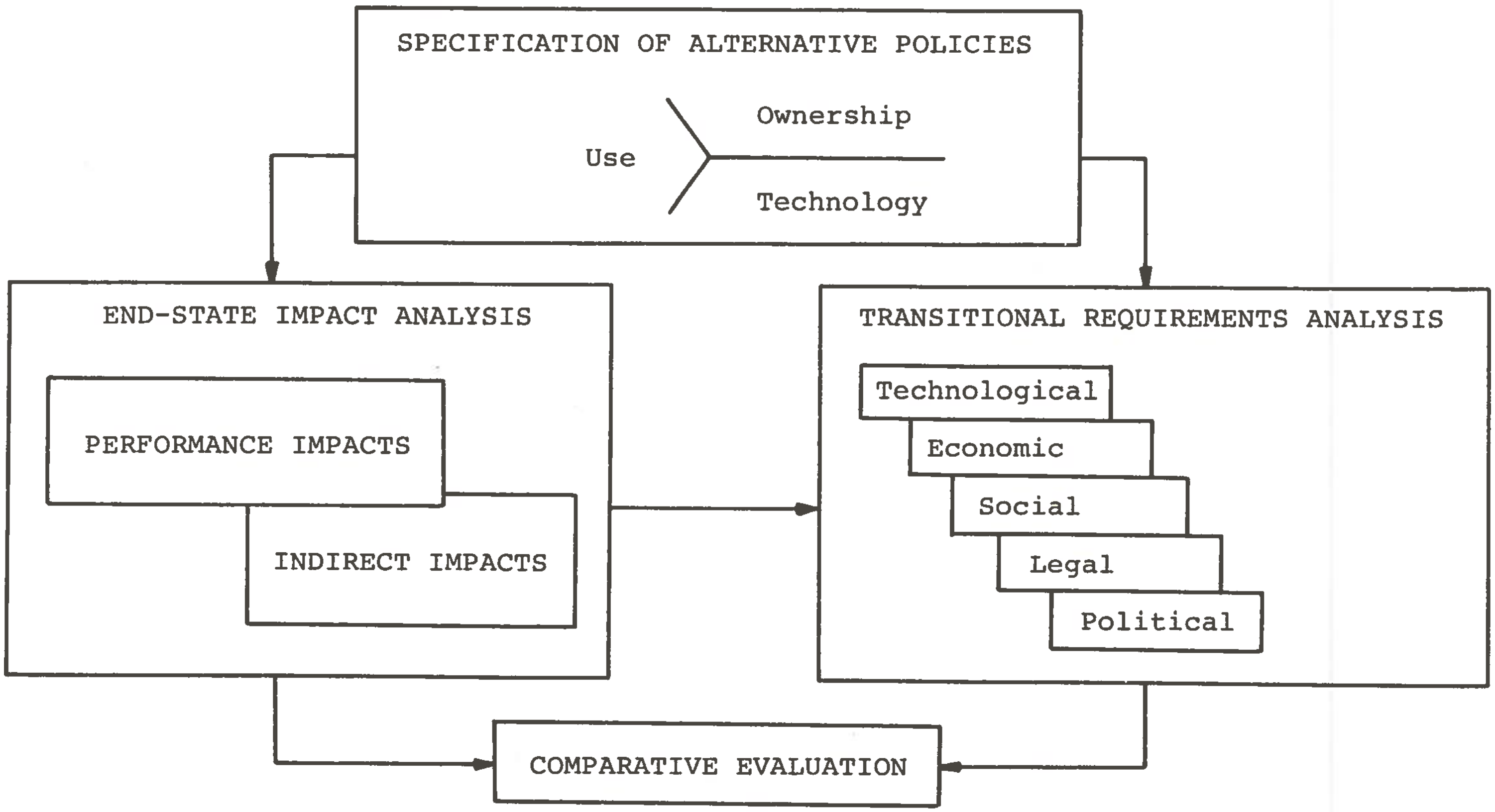

Figure 1. Central Elements of Project Mission

The project work plan consists of nine major tasks which follow a generally sequential pattern (see Figure 2). The following discussion explains the basic rationale for particular tasks and key interfaces. For this purpose it is most convenient to work backwards from the rightmost part of the figure, in terms of the three groupings indicated.

The entire work plan points toward the formulation and analysis of specific policy alternatives in accordance with the project mission. The three rightmost boxes in the figure correspond to the last three tasks within the formal work plan:

| | |
|---|---|
| Task 7 | Development of Alternative Policy Scenarios |
| Task 8 | End State Impact Analysis |
| Task 9 | Transitional Requirements Analysis |

Relationships between these endeavors have been discussed earlier.

Tasks 5 and 6 serve a function of providing benchmark guidance for the development of alternative policy scenarios in Task 7:

| | |
|---|---|
| Task 5 | Existing Baseline Analysis |
| Task 6 | Analysis of (Reference) Alternatives |

Task 5 involves an analysis of the "do-nothing" or "Null" alternative (assuming 1976 technology, standards, and

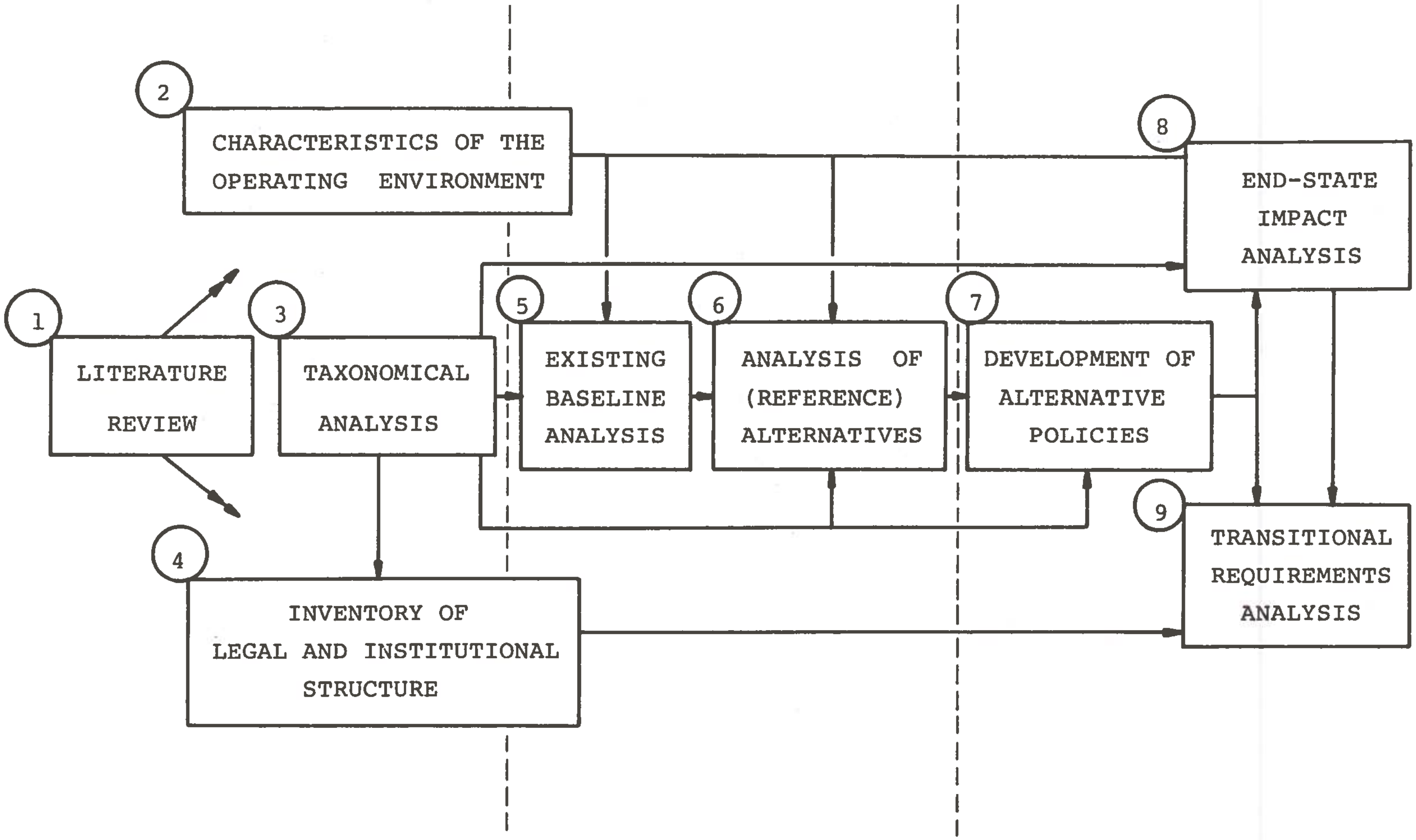

Figure 2. Summary of Task Sequence and Interfaces

policies). Its scope is restricted to end-state impact analysis (Task 4 will engage in some projection of legal and institutional structure for "do-nothing" circumstances, as pertinent to transitional requirements). The immediate concern in Task 5 is with performance effects, although sufficient attention must be given to indirect effects to provide a benchmark of comparison for later analyses of alternative policies. As will become evident below, this analysis of the "do-nothing" alternative will draw directly (like the end-state impact analysis of Task 8) upon the characterization of "operating environments" in Task 2.

Task 6 is a kind of microcosm of Tasks 7 through 9 since it develops and analyzes alternatives. However, its distinction from these later tasks lies in its restriction to "partial" policy solutions directed to individual shortcomings of automotive transport (as projected in Task 5 under "do-nothing" circumstances). As such, it purports to yield strategies which are, e.g., strong candidates for reducing congestion, or for reducing accident/damage risk, or for reducing air pollution, or for reducing energy consumption, etc.

In this endeavor several alternative strategies will be examined with regard to each performance shortcoming, and the strength of candidacy for each will be assessed in terms of performance impacts. In effect, this task focuses on the identification of piecemeal strategies and filters those strategies by means of preliminary engineering analyses. The results of this endeavor will provide building-block insight into the in-depth development of composite or integrated policy scenarios in Task 7.

The remaining tasks involve endeavors which are prerequisite to any development and analysis of alternative (including the "do-nothing") policies:

| | |
|---|---|
| Task 1 | State-of-the-Art Literature Review |
| Task 2 | Characteristics of the Operating Environment |
| Task 3 | Taxonomical Analysis |
| Task 4 | Inventory of Legal and Institutional Structure |

Task 1 is self-explanatory and its results are giving state-of-the-art guidance to all other tasks. Task 2 serves the function of defining relevant "exogenous" conditions for the study, in the form of typical operating environments for automobile use (and ownership). This function takes on two manifestations: defining the structure and determinants of typical travel patterns, and defining background levels for certain performance effects and mass transport availability. For these purposes three distinct aspects of the operating environment require detailed specification:

(a) Trip structure and its underlying determinants (economic, demographic and land use patterns, and personal preferences or values toward travel)

(b) Levels of non-automotive transportation availability
(c) Background levels of air and noise pollution from non-automotive sources

This task requires special care to define those characteristics of typical operating environments as conditions to be treated as constant over all policy alternatives we eventually explore.* These operating environments are being synthesized for large-urban and rural areas for 1980, 1990 and 2000. The specification of trip structure and its determinants, and of non-automotive options, feeds directly into Task 5 as noted and into later analyses of performance impacts (both in the preliminary engagements of Tasks 5 and 6 and in the high-gear endeavor of Task 8). The specification of background levels and non-automotive transport options is of interest to the eventual comparative evaluation of alternative policies.

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* - Meeting this requirement will necessitate some judicious assumptions. Certainly some aspects of an operating environment (e.g., birth rate) are readily identified as independent of our policies. However, other aspects (e.g., long-term land use shifts and even personal preference structures) undoubtedly may exhibit adjustments in response to particular policies. To some extent we must idealize such factors as being independent of alternative policies purely to control the scope of analysis (i.e., leave for future study the relaxation of the fixed land-use assumption).

A problem area of this nature brings to mind a bewildering array of policy strategies and potential impacts, the purpose of Task 3 (Taxonomical Analysis) is to develop exhaustive and reasonably unambiguous classifications for these two concerns. Some hint of basic structures for each concern has been advanced in our earlier remarks on alternative policy strategies. As for interfaces, the policy taxonomy feeds directly into Task 4 (see below) and into Tasks 6 and 7 (where actual alternatives are generated either for preliminary or indepth analysis). The impact taxomy likewise feeds into Task 4 (see below( and into Tasks 5, 6 and 8 (since these latter three tasks involve either preliminary or in-depth impact analysis).

Task 4 (Inventory of Legal and Institutional Structure) is critical to the proper consideration of transitional implementation issues. Entirely preparatory to the eventual requirements analysis in Task 9, this effort has multiple functions:

(a) develop an inventory of legislation, bureaucratic roles and relationships, and rooted economic/social structures (as evident today) which might be taxed by the policies we develop

(b) speculate on likely changes in (a) through the future (a kind of "Null" projection of legal and institutional structure)

(c) study potentially applicable foundations for prescribing transitional mechanisms; i.e., parallels in history, in international experience, or in political theory.

## COLLABORATIVE RELATIONSHIPS

The Office of University Research encourages direct colaborative and cooperative relationships between its progress to research efforts and ultimate client interests in both the public and private transportation sectors. As part of the Pitt study we have secured the formal collaboration of the Ford Motor Company and the Allegheny County Department of Planning and Development, and are building upon established relationships with other local and state planning agencies. Also, approximately thirty outside representatives of pertinent interests will be informed regularly of progress to obtain additional reaction. Hopefully this overview of our efforts will provide the initial impetus for cooperative relationships with the Automotive Energy Efficiency Program.

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# EVALUATION OF METHYL ALCOHOL AS A VEHICLE FUEL EXTENDER

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## ABSTRACT

Methal alcohol (methanol)-gasoline blends, a potential automobile fuel, are examined. Two series of tests are described. The first, the single cylinder engine test program, consisted of two distinct efforts — an evalution of the effect of methanol on base gasoline octane ratings, and a parametric study of the effect of methanol on emissions and fuel economy. The second test series, conducted on an existing engine and drive train modified to simulate a 1974 vehicle, used a chasis dynanometer to measure emissions levels and fuel economy.

Basic conclusions were that (1) no substantial improvement in octane was observed in methanol-added unleaded gasoline, (2) methanol-gasoline blends of up to 10 percent could be used without major changes in emissions or fuel economy, and (3) operational problems may exist.

## INTRODUCTION

When this project was initiated in the spring of 1974, the idea that methyl alcohol or methanol could readily be made from coal or waste materials raised the question concerning the effects of using this fuel for transportation energy. Specifically, could methanol be used in automobiles, and if so, what were the advantages and problems associated with its use.

Two approaches to using methanol in automobiles were obvious: 100% methanol could be used for controlled fleet operations and free petroleum base fuels for non-fleet use; or blend methanol with gasoline to "extend" the liquid petroleum fuel supply.

The work in this study was limited to examining methanol-gasoline blends. The examination was separated into two basic objectives. The first objective was to characterize the emissions, fuel economy, and performance of methanol-gasoline blends in an equivalent late model vehicle (1974 model year) using the federal test procedure (FTP) specified in the emission certification procedure. The second objective of the work was to characterize the behavior of methanol-gasoline blends at equivalent operating conditions to determine potential advantages or problems associated with the blended fuels.

## SINGLE CYLINDER ENGINE PROGRAM

The single cylinder engine test program was subdivided into two distinct efforts. The first portion of this work was a program to evaluate the effect of methanol on the octane rating of the base gasoline. Many proponents of methanol-gasoline blends cited the "octane boosting" effect produced by the addition of methanol to gasoline. The octane evaluation program was designed primarily to evaluate the effect of methanol on the octane rating of unleaded gasolines. For this program four unleaded base fuels, ranging in Research Octane Number from 81.1 to 98.1, were used.

Table 1 describes the properties of these base fuels. The methanol concentration was varied from 0 to 100% for the tests. (The concentration of methanol is expressed on a volume basis, before the constituents are blended).

Figure 1 is representative of the results obtained from the octane test program. This figure is typical for a low octane base fuel. Note that a substantial improvement in the Research Octane Number (RON) is produced by the addition of methanol. The Motor Octane Number (MON) is not improved so substantially by the addition of methanol. Figure 2 illustrates the results obtained for a relatively high octane base fuel. The increase in the RON is not nearly as pronounced as for the low octane fuel and the MON shows essentially no change. Since the MON is a more important indication of the octane requirements of modern American vehicles with automatic transmission, the real octane improving characteristics of methanol added to gasoline are relatively minor.

In order to better distinguish the relative effect of methanol on the octane ratings on the different base fuels used, the Blending Octane Value of the methanol was examined. It was found to be a strong function of the methanol concentration and thus not suitable for describing base fuel effects. A crude parameter, related to the asymptotic value of the octane vs. % methanol curve, was developed. This parameter, called ΔN, could be directly calculated from each characteristic curve of octane vs. % methanol. Figure 3 illustrates the relationship between the parameter, ΔN, and the octane rating of the base fuel. Clearly these data indicate that the octane improving characteristics of methanol are greatly reduced as the octane rating of the base fuel is increased. For base octane ratings corresponding to currently available fuels, the octance improving characteristics of methanol are very minor.

The conclusion that can be drawn from the octane study is that the addition of methanol does not substantially improve the over all octane rating of modern unleaded gasolines. There is some increase in the RON rating of the fuel due to the addition of methanol; however, increases in the MON rating are negligible. This behavior indicated that increases in engine compression ratio could not be justified by an anticipated increase in octane rating due to the addition of methanol. The remainder of the single cylinder engine test program was planned with these results in mind.

## TABLE 1. GENERAL BASE FUEL CHARACTERISTICS

| Characteristic | Base Fuel A | Base Fuel B | Base Fuel C | Base Fuel D |
|---|---|---|---|---|
| General Description | Summer blend of regular grade gasoline without TEL | Summer blend of regular unleaded gasoline commercially available | Summer blend of premium type unleaded gasoline for 1975 & later vehicles | Indolene (14) unleaded, reference fuel specified for use in vehicle emission certification |
| RON | 81.1 | 89.9 | 95.8 | 98.1 |
| MON | 75.5 | 82.1 | 87.1 | 87.6 |
| Nominal HC Distribution (%) | | | | |
| Olefins | 1.0 | 12 - 15 | 1.0 | 10 |
| Aromatics | 31.0 | 20 - 25 | 27.5 | 35 |
| Saturates | 68.0 | 68 - 60 | 71.5 | 55 |
| ΔN (RON) | 30.35 | 20.85 | 14.05 | 12.00 |
| ΔN (MON) | 10.65 | 4.10 | 1.96 | 0.66 |
| K (RON) | 0.02759 | 0.02583 | 0.03426 | 0.02896 |
| K (MON) | 0.03743 | 0.02919 | 0.0251 | 0.0345 |

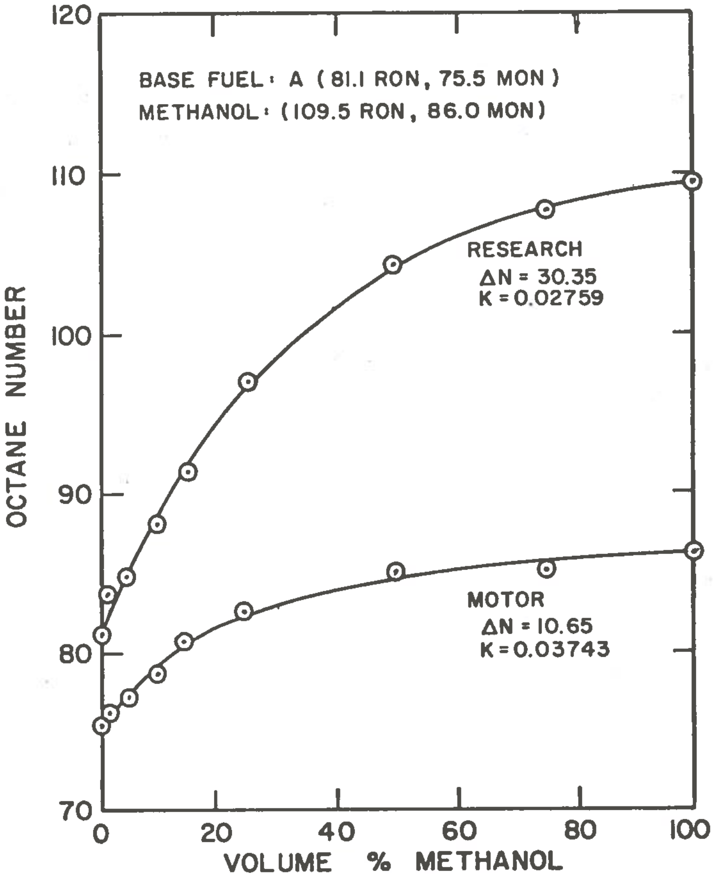

Figure 1. Blend Octane Characteristics, Base Fuel A and Methanol

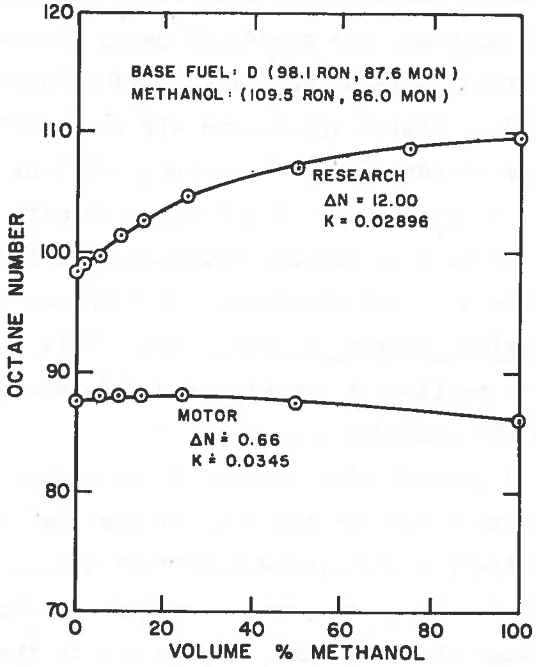

Figure 2. Blend Octane Characteristics, Base Fuel D and Methanol

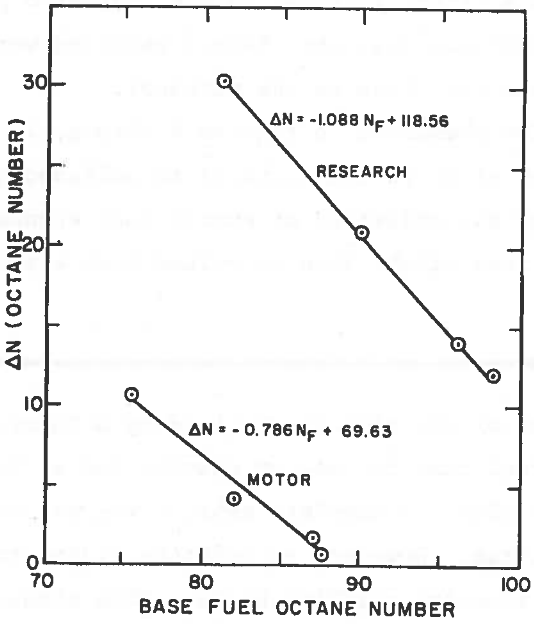

Figure 3. Correlation Between Octane Increment and Base Fuel Octane Number

A parameter study using two unleaded base fuels and these same fuels with the addition of 10% methanol was conducted using a modified CFR engine. Engine modifications were primarily related to providing controlled operation at a wide range of engine speeds and air-fuel (A/F) ratios. Data were taken at four engine speeds, four A/F ratios, and four spark timing settings for two base fuels and blends of 10% methanol with these base fuels. These data were reduced to provide emissions and fuel economy information that would allow a direct comparison of the base fuel and the methanol blend for equivalent operating conditions. This comparison was intended to point out any particular advantages or disadvantages to the addition of methanol to the unleaded gasoline.

Figures 4 through 13 present the results of the single cylinder engine study. The results presented are for the fuel system that used Indolene as the base fuel. The results for the second base fuel system were essentially similar and represented, for the most part, redundant information. The greatest difference between the base fuel systems due to the addition of methanol was observed for the Nitric Oxide emissions. The addition of methanol to the Indolene fuel system produced a slight reduction in the peak NO emissions. Conversely, the addition of 10% methanol to the second base fuel system caused a slight increase in the indicated peak NO emissions. These results seem to indicate that the changes observed were due more to the character of the base fuel than to the methanol.

From the information presented in figures 4 through 13 it can be concluded that the addition of up to 10% methanol to unleaded gasoline does not substantially change the emissions or energy fuel economy at equivalent operating conditions. Some slight loss in volume fuel economy could be anticipated.

## SIMULATED VEHICLE TESTS

A proper evaluation of the effects of blending methanol with gasoline for use as automotive fuel must include an examination of how that fuel will operate in existing vehicles. A complete vehicle was not available for this portion of the test program. However, an existing engine and drive train system was modified to simulate a 1974 vehicle. This simulated vehicle was operated on a chassis dynamometer using the federal Urban Driving Schedule to evaluate the emissions and fuel economy behavior of the base fuels and

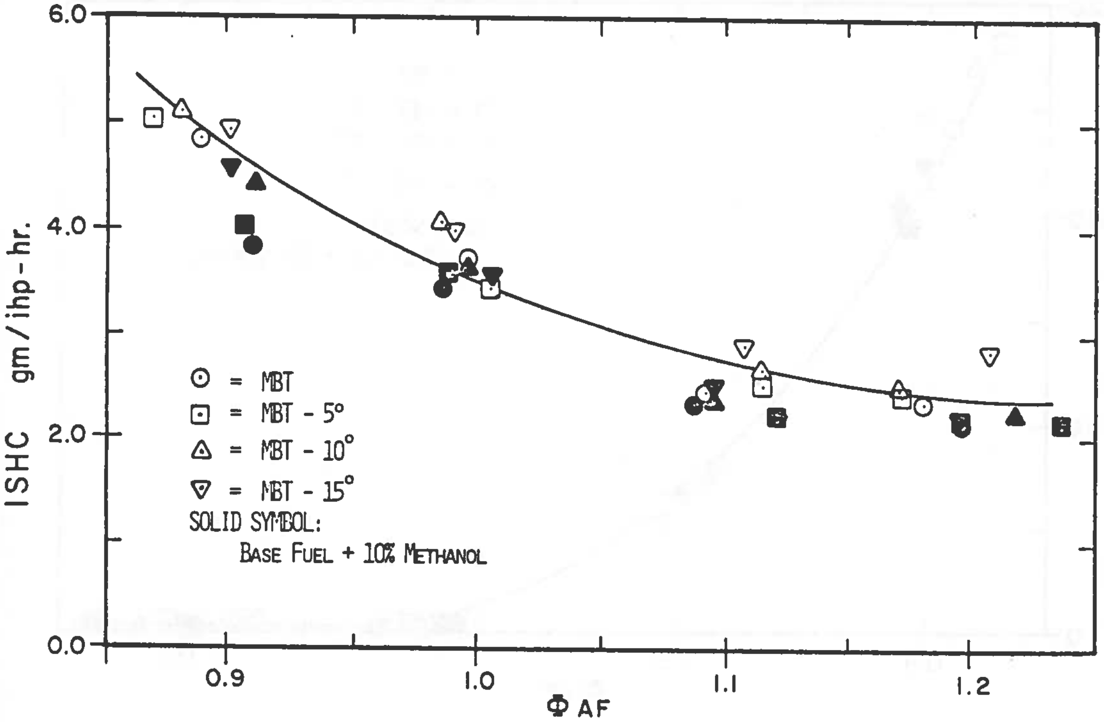

Figure 4. Indicated Specific HC, Indolene Base Fuel, 600 RPM

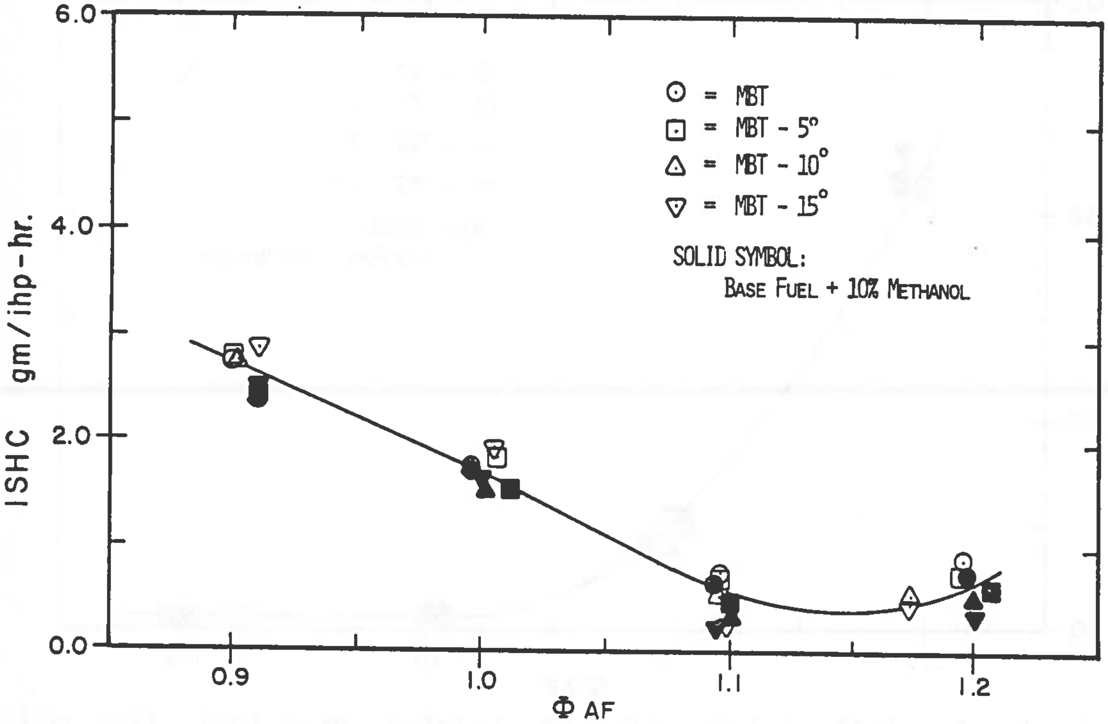

Figure 5. Indicated Specific HC, Indolene Base Fuel, 1800 RPM

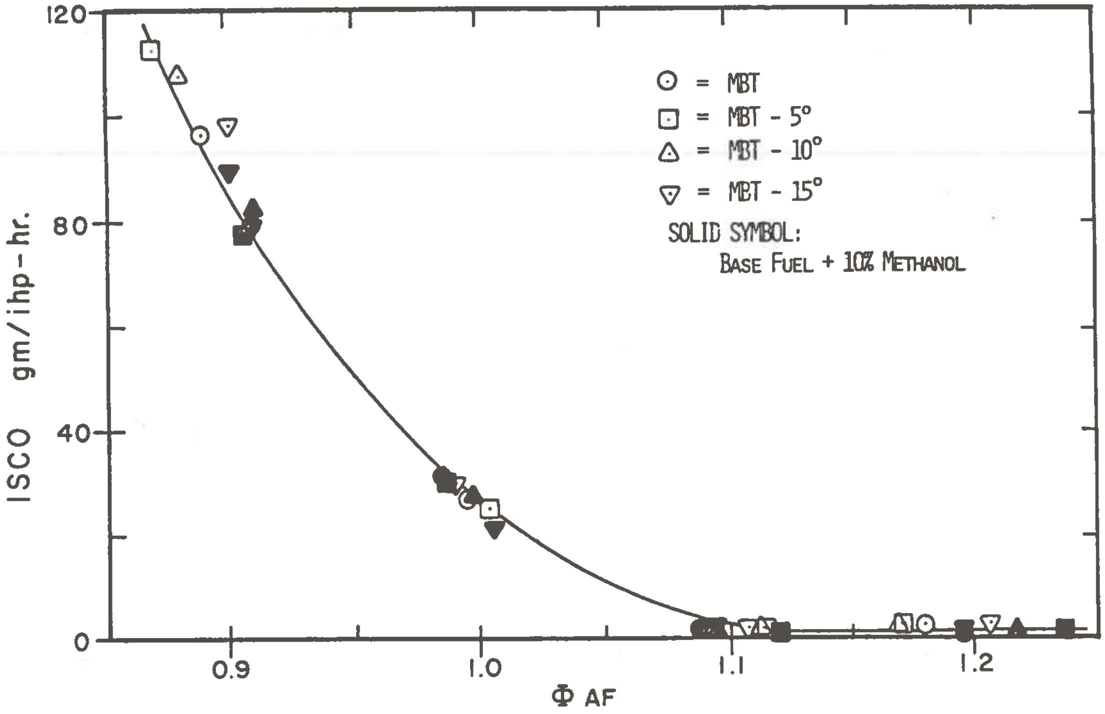

Figure 6. Indicated Specific CO, Indolene Base Fuel, 600 RPM

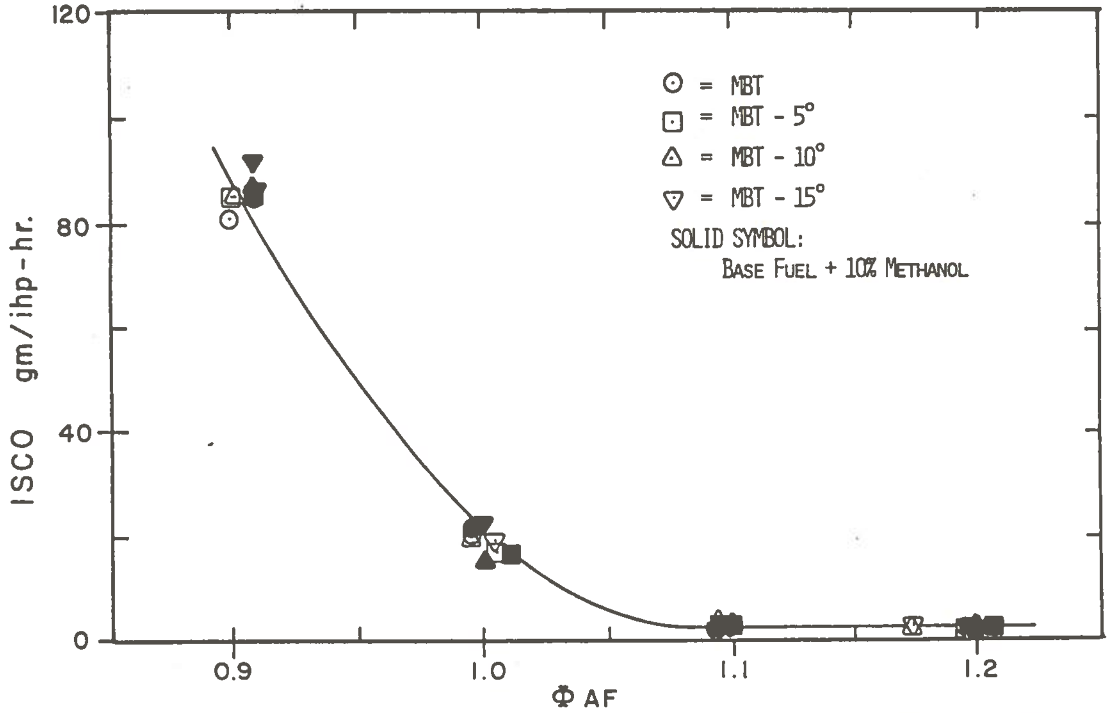

Figure 7. Indicated Specific CO, Indolene Base Fuel, 1800 RPM

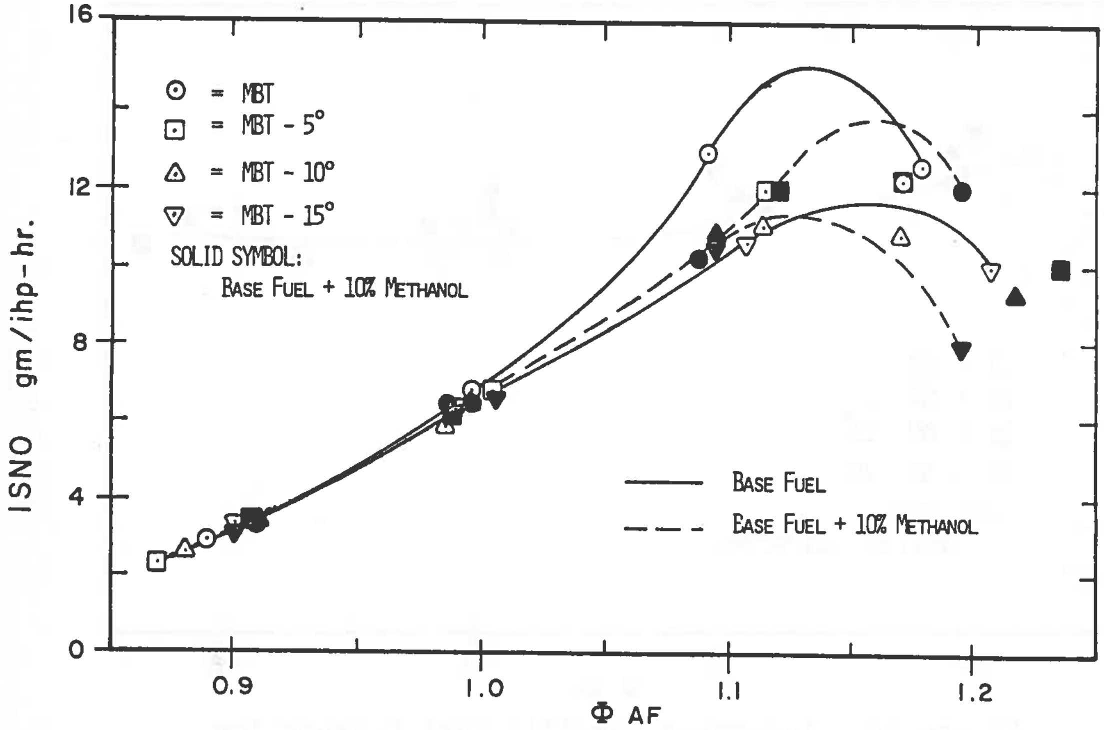

Figure 8. Indicated Specific NO, Indolene Base Fuel, 600 RPM

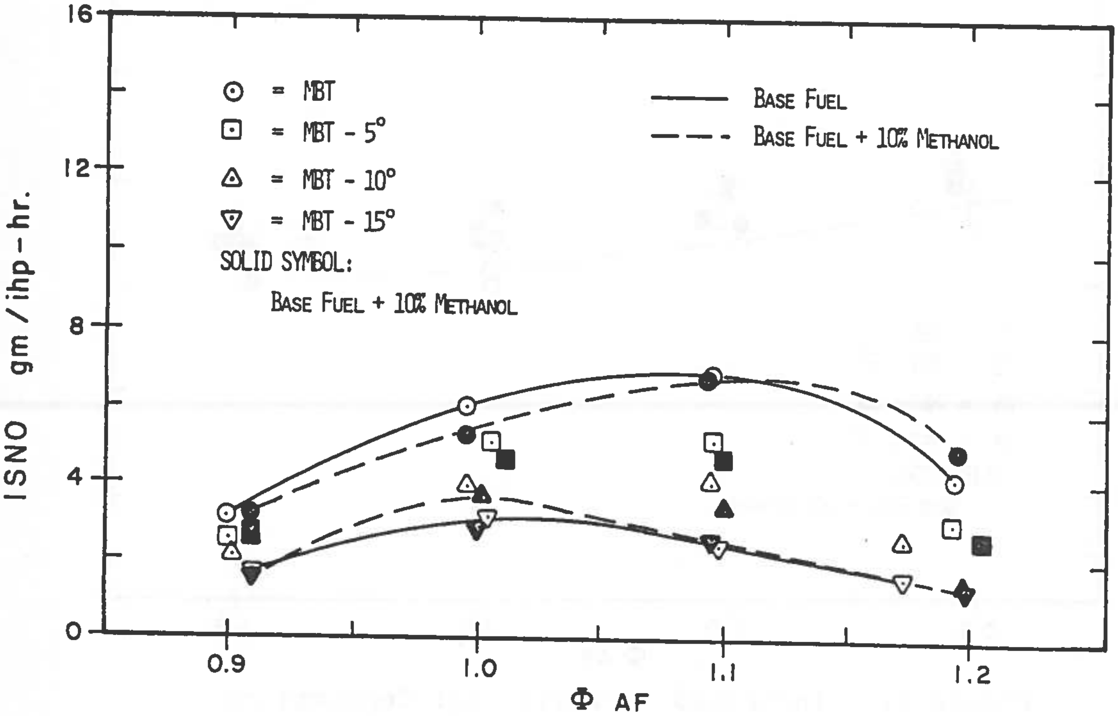

Figure 9. Indicated Specific NO, Indolene Base Fuel, 1800 RPM

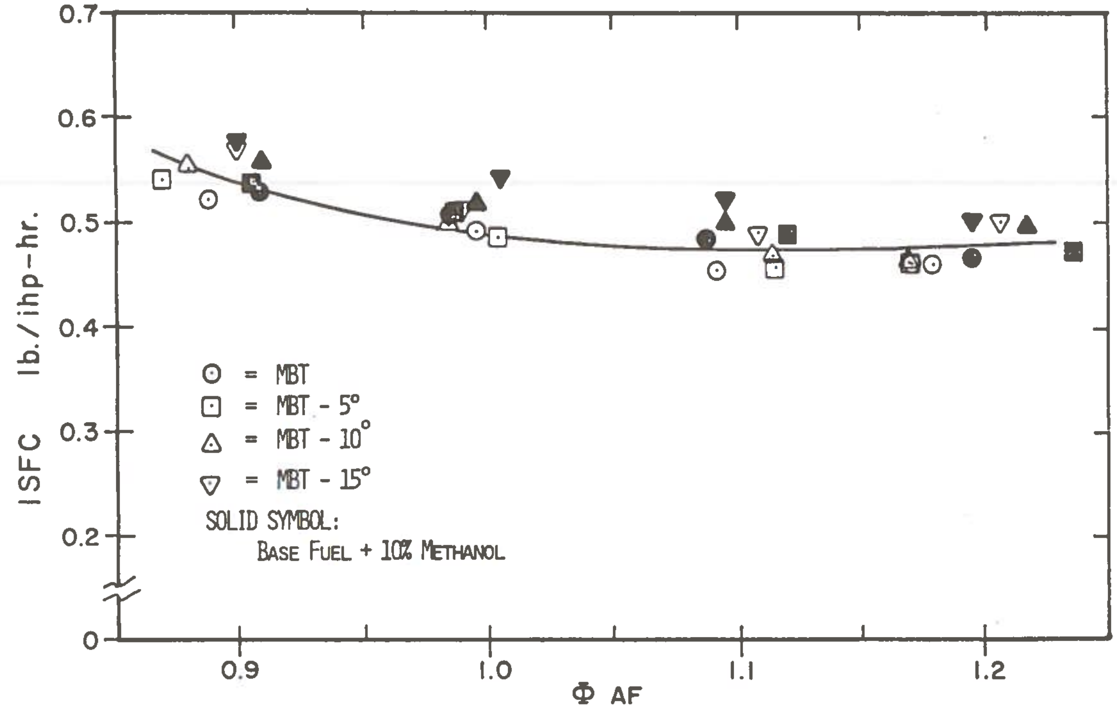

Figure 10. Indicated Specific Fuel Consumption, Indolene Base Fuel, 600 RPM

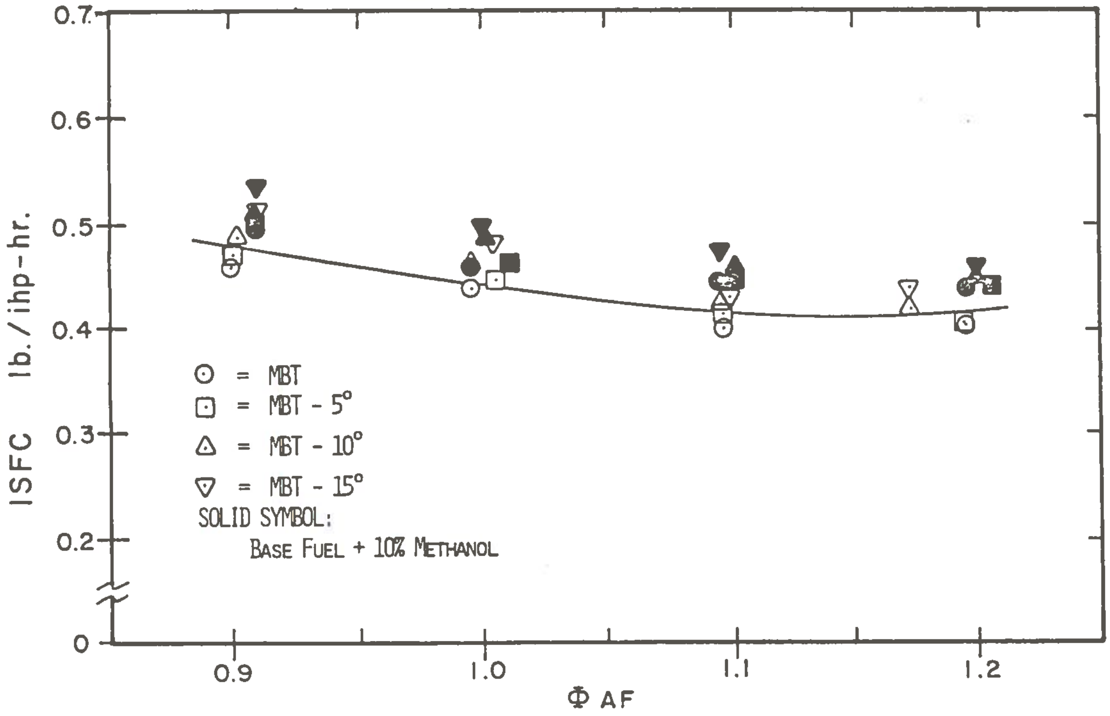

Figure 11. Indicated Specific Fuel Consumption, Indolene Base Fuel, 1800 RPM

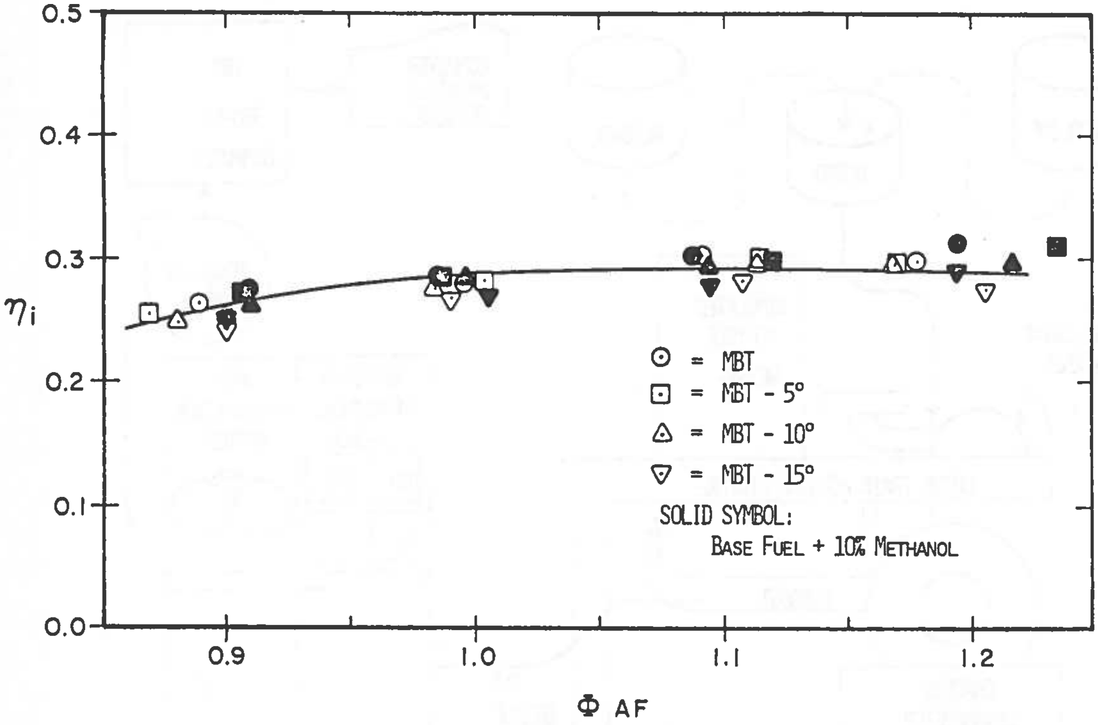

Figure 12. Indicated Thermal Efficiency, Indolene Base Fuel, 600 RPM

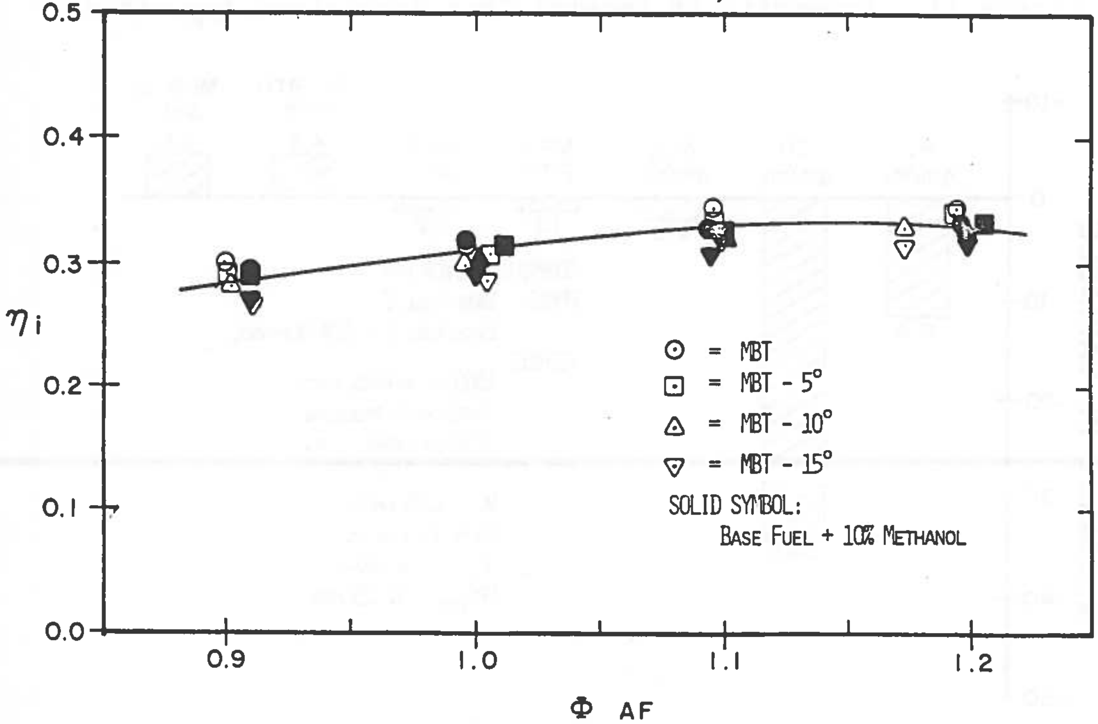

Figure 13. Indicated Thermal Efficiency, Indolene Base Fuel, 1800 RPM

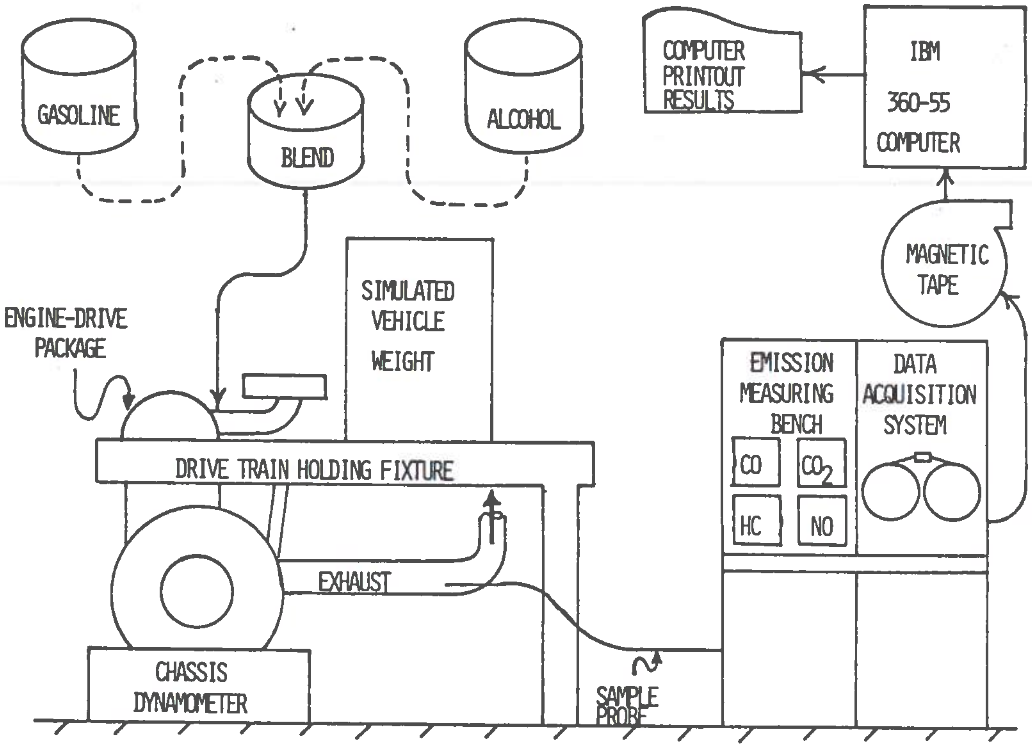

Figure 14. Schematic of Federal Test Simulation Apparatus

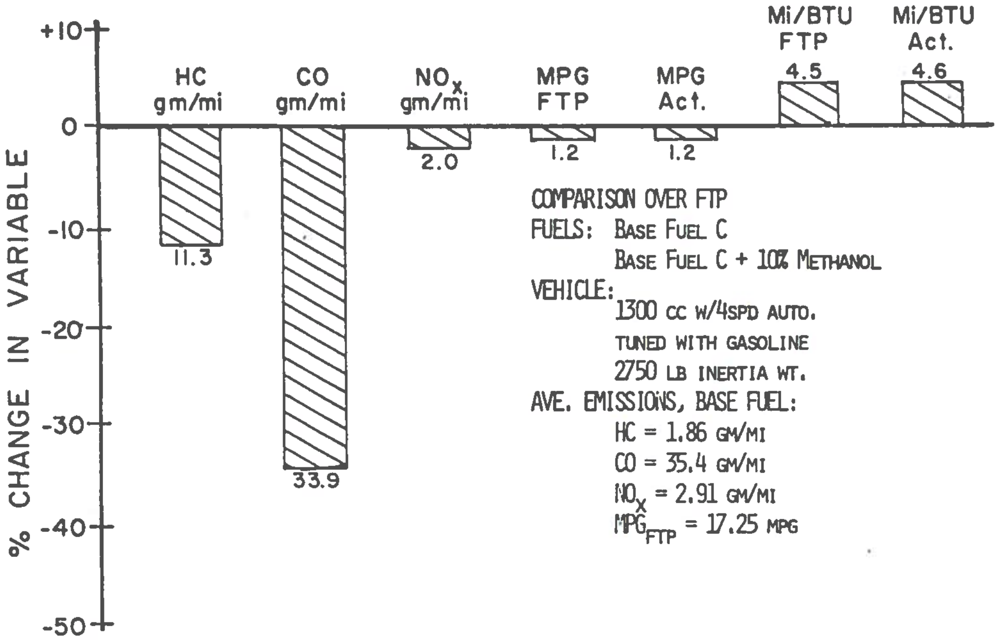

Figure 15. Changes in FTP Results for 10% Methanol Added to Base Fuel C

base fuel - methanol blends. A modal analysis system was used to determine the federally specified emissions, in grams per mile, from a continuous analysis of the exhaust emissions and other vehicle variables. A schematic of the system used is given in figure 14.

Figures 15 and 16 are bar graphs of the differences obtained between operating the "vehicle" with the base fuel and with the base fuel plus 10% methanol. The information presented in these figures represents the average of three or more CVS-CH runs. The engine-drive system was not altered from the calibration used to achieve emissions equivalent to a 1974 automobile. Examination of figures 15 and 16 indicates that the addition of 10% methanol to the unleaded fuels tested substantially reduced the CO emissions but had little effect on HC and $NO_x$ emissions. Fuel economy was changed only slightly. The reduction in CO emissions can be almost entirely attributed to the effective leaning of the air-fuel mixture by the addition of methanol. Subjective observations indicated that the 10% methanol blend caused some driveability problems during the first few minutes of the cold start portion of the driving cycle. Most of these problems could also be attributed to the effectively leaner air-fuel mixture for the methanol blend.

In an attempt to improve the operation of the "vehicle" using the 10% methanol-gasoline blend, the results of the single cylinder engine study were used to indicate suitable changes in spark timing and air-fuel mixture. The only changes that were considered allowable were those that could be easily accomplished by any service station mechanic. Using these limitations, the basic spark timing of the engine was advanced 5 degress to account for the effectively leaner mixture of the methanol blend and the idle speed and CO concentration were adjusted to those used for the baseline 1974 vehicle. Figure 17 illustrated the changes produced by these adjustments to the engine. CO emissions were reduced from the baseline engine configuration, fuel economy was improved, and $NO_x$ emissions were increased. The improved fuel economy and increased $NO_x$ emissions are attributed to the 5 degree spark advance. In addition to the changes in emissions and fuel economy the driveability of the "vehicle" was greatly improved by the engine adjustments.

The results of the simulated vehicle tests can be summarized as follows: The addiiton of 10% methanol to unleaded gasoline can reduce the CO emissions for a 1974 model year vehicle. HC, $NO_x$ emissions, and fuel economy were

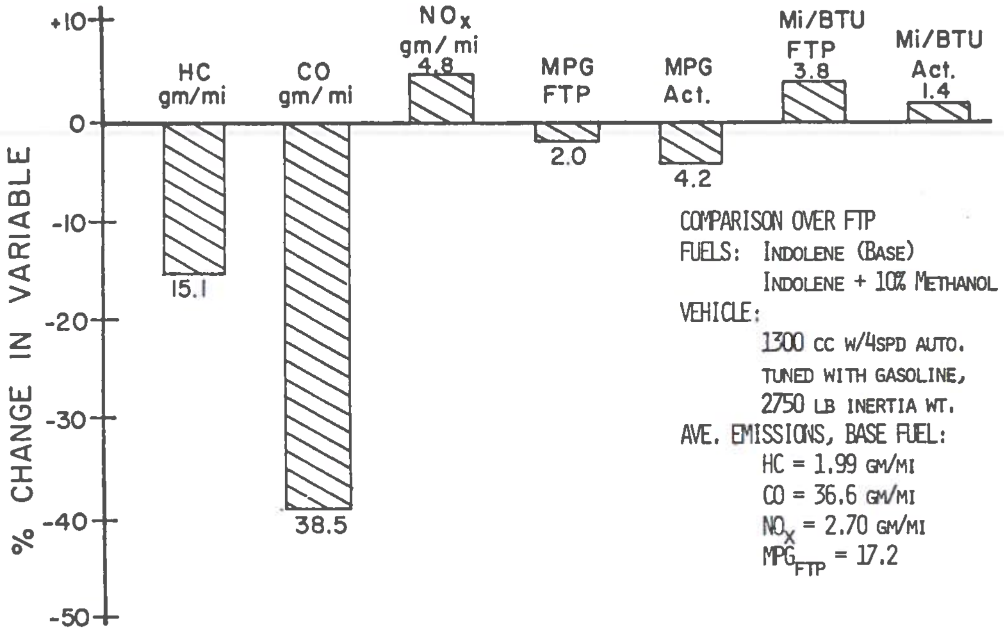

Figure 16. Changes in FTP Results for 10% Methanol Added to Indolene

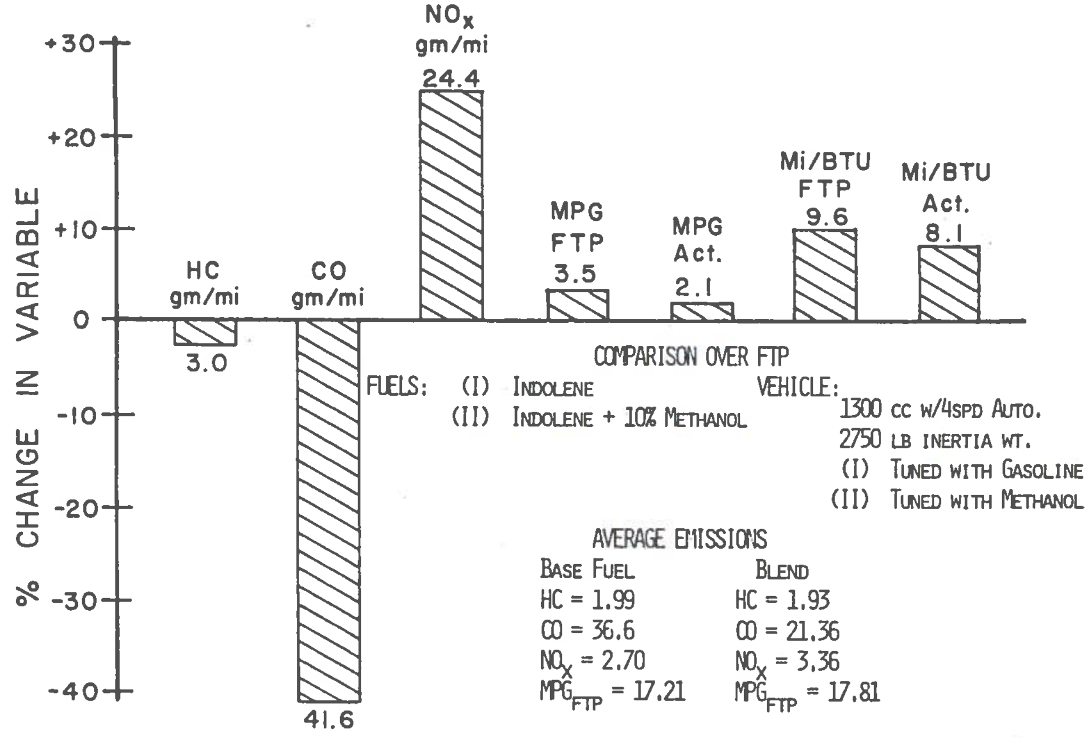

Figure 17. Changes in FTP Results for Returned Engine, Methanol Blend Vs. Base Fuel

changed only slightly by the addition of 10% methanol. Retuning the engine to provide better operation using the methanol-gasoline blend can improve fuel economy but at the cost of increased $NO_x$ emissions.

## CONCLUSIONS

The basic conclusions that can be drawn from this evaluation program are that blends of up to 10% methanol with gasoline could be used in the existing automotive fleet without major changes in emissions or fuel economy. However, there could be operational problems associated with the corrosion characteristics and water solubility problems demonstrated by methanol-gasoline blends. The 10% methanol-gasoline blend would be a viable alternative to fuel shortages.

# DEVELOPMENT OF THE VALVED HOT-GAS ENGINE

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## ABSTRACT

The MIT valved hot-gas engine (VHGE) is a closed-regenerative-Brayton cycle engine using helium or hydrogen as the working fluid and employing a reciprocating compressor/expander. By utilizing a low molecular weight gas at a high mean pressure and high power density (similar to Stirling cycle engine), high efficiency can be achieved with moderate heat transfer surface. The VHGE has the low pollution and multifuel capability of an external combustion engine, and will be able to offer high efficiency under frequent and rapid changes in power as required in vehicle applications by means of variable valve timing.

An experimental, one cylinder apparatus was built and has been tested in the low power, low speed range to obtain maximum design information. During the past year, a new electric heater was designed and constructed in preparation for maximum power operation. Work on variable valve timing was initiated.

The most significant results during the period were based on the results of test runs which included the measurement of transient gas temperature inside the cylinders using specially designed fast response thermocouples. With the more complete P-V-T data available, mass and energy balances were made for each engine component taking into account the leakage past piston rings and valves. From these, it was concluded that the observed non-ideal performance of the test apparatus was largely due to excessive enthalpy flux into the compressor associated with piston ring leakage. Additional experiments will be needed to confirm above conclusions.

An unsteady state analysis of the VHGE operation, combined with the results from mass balance and energy balance indicated that wall-to-gas heat transfer inside the compressor could have a significant effect on engine efficiency. The installation of an additional cooling water jacket around the compressor cylinder increased the indicated efficiency from 18% to 22%.

Based on the improved understanding, a series of new modifications for the experimental apparatus are under consideration which are expected to significantly improve the VHGE performance, and establish a basis for a rapid advancement toward the full potential of the VHGE.

# INTRODUCTION*

A new valved, hot-gas engine (VHGE) has been under investigation at M.I.T. since 1969. The VHGE is a closed-regenerative-cycle engine which uses helium as the working gas and employs a reciprocating expander/compressor.

The operation closely follows an ideal Brayton cycle. Hot, high pressure gas from the burner/heater is expanded nearly reversibly and adiabatically in the expander. Low pressure exhaust gas from the expander is first cooled in the regenerative heat exchanger and then in the cooler. Cool low-pressure gas from the cooler is compressed nearly reversibly and adiabatically in the compressor. The high pressure gas is then preheated in the regenerative heat exchanger and then heated to maximum temperature in the burner/heater.

In the final developed configuration,the engine is expected to have multiple expander/compressor cylinders (perhaps four) connected with a single heater, a single regenerative heat exchanger, and a single cooler, each operating with steady (rather than pulsating) gas flow. This is one of the advantages of the VHGE over the multicylinder Stirling cycle engine which requires a separate set of heat exchange components for each cylinder. By utilizing a low molecular-weight gas flowing steadily at a high mean pressure, the VHGE can achieve a high power density, and a high efficiency of about 40% with a moderate requirement for heat transfer surface. The VHGE has the low pollution and multifuel capability of an external combustion system. In addition, preliminary work has indicated that the VHGE system should be able to offer high efficiency under frequent and rapid changes in power as required in vehicular applications. The concept is to use variable valve timing to reversibly vary the mass of gas circulated, rather than using an irreversible pump-up, blow-down system to change the gas charge in the engine as is used in the Stirling cycle engine. Another potential advantage of the VHGE over the Stirling cycle engine is that VHGE heats expander inlet gas and cools compressor inlet gas directly, which reduces the heat load and temperature span on the regenerative section.

A model for calculating the performance of a VHGE was developed employing steady state analysis of the engine operation based primarily on ideal Brayton cycle. An experimental one cylinder VHGE was built and has been tested in the low speed and low power range.

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*This paper consists of the Executive Summary of Joseph L. Smith, Jr., "Development of the Valved Hot-Gas Engine," U.S. Department of Transportation, Office of the Secretary, Office of University Research, Washington DC, August 1975, DOT-TST-76-34.

## PROBLEM STUDIED

### 1) Improved Analysis of VHGE

The preliminary, low power,low speed tests of the experimental engine performance did not come up to expectations. The efficiency was 13%, much lower than was predicted, and compressor work was 1.8 times the expected. Mass flow rates calculated from P-V diagrams and average temperatures measured outside the cylinder were not self consistent. A considerable, yet unknown amount of leakage seemed to exist past the piston rings. There arose a need for an improved analysis to predict the performance of the existing engine, and establish a basis for future design.

A preliminary unsteady analysis was undertaken. The unsteady state energy equation was integrated step by step for each processes inside the cylinder accounting for the leakage and wall-to-gas heat transfer. The analysis revealed the need for more detailed data. Additional instrumentation and experiments were required, specifically transient temperature measurements inside the cylinder, using fast response thermocouples.

### 2) Increase the Opertional Range of the Experimental Engine

A new heater was needed because the existing heater had a power of 15KW, only one fourth of the maximum power requirement of the engine.

### 3) Investigate Variable Valve Timing

Practical methods of achieving variable valve timing for power control in the VHGE were to be sought and evaluated.

### 4) An Optimized Design for a VHGE

This task was planned for the second year of the program.

## RESULTS ACHIEVED

1) The operation of the engine and the analysis were reconciled as the result of improved analysis and additional data on the internal processes inside the cylinder.

In particular, the apparent discrepancies in flow rates were resolved by actual measurements of gas temperature as a function of time inside the cylinder.

Utilizing transient temperature data, an analysis was developed to follow the processes in the cylinder more closely. This was applied to the experimental engine, and the calculated leakage rates are as follows: from expander to compressor, 15%, from compressor to expander, 10%,of the average mass flow rate of the engine. The analysis also showed that the temperature of the gas leaking into the compressor was much higher than the average gas temperature of the compressor. The analysis showed that the piston ring leakage has two effects. One is the direct power loss due to the mass of the leaking gas, the other is the increase in effective gas compression temperature caused by the enthalpy flux associated with hot gas leaking into the compressor.

Limiting case heat transfer analyses and experiments suggested that improved cooling of the compressor wall would increase the compressor efficiency, especially volumetric efficiency, thus reducing the compressor work. In fact, tests showed the expected decrease in compressor work, and an increase in indicated efficiency from 18% to 22% by the additional cooling.

2) A new heater was designed and constructed to increase the power input to the VHGE from 15KW to 60KW. This will allow the maximum operation of the experimental engine. The heater is now complete and ready to be installed.

3) Various methods of variable valve timing were investigated. Two promising mechanisms were carried to the preliminary design stage. The first is a dual-cam hydraulic-lifter system with one rotatable cam for valve timing. The second is a single fixed cam system with a variable angular-velocity mechanism for valve timing.

## UTILIZATION OF RESULTS AND CONCLUSION

The work done under the contract has confirmed the projected potential of the engine by identifying the mechanisms causing lower than expected performance of the experimental engine. The theoretically projected efficiency and power control potential is supported by analyses and experiments performed. The next steps in the realization of the potential of the engine have been defined.

The potentials justify continued work to develop a practical engine with the objective of increased fuel economy and reduced emission. The results of the research indicate the engine is a candidate for inclusion in the ERDA alternative automobile engine development program.

# FLYWHEEL AUTOMOBILE DESIGN AND SIMULATION AND THE DEVELOPMENT OF A TRANSIENT EMISSIONS MODELING TECHNIQUE

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University of Wisconsin-Madison

## ABSTRACT

Tentative results of several ongoing flywheel vehicle projects are reported. A demonstration vehicle currently under construction that will use a powerplant incorporating a high-speed energy-storage flywheel is described. The demonstariton vehicle design will incorporate a flywheel, a flywheel power plant, and a continuously variable transmission. Also presented are results of a computer simulation of a flywheel technique. Finally, a description is given of a new technique of modeling transient emissions, employing a new set of data, the Dynamic Average Emissions Flow Tables, in place of the steady-state emissions data from engine dynanometer tests.

## Overall Program and Objectives

The purpose of this paper is to report on the results that have occurred since the last AEEP Coordination meeting in the research program entitled "Increased Fuel Economy in Transportation Systems By Use of Energy Management", sponsored by the Office of University Research of the U.S. Dept. of Transportation.

The basic objective of the 3-year program is to study and evaluate methods for improving fuel utilization efficiency in automobiles. The methods being emphasized are those based on Energy Management, a term applied to advanced powerplant concepts in which the generation, storage, and application of energy for the propulsion of the vehicle is done in a manner which will optimize the overall fuel efficiency for a given driving cycle.

## Past, Current, and Future Research

Earlier work in the program has consisted of the development of detailed computer simulation techniques and programs for the study of the fuel consumption and emissions characteristics of standard cars, the investigation of straightforward drivetrain variations on fuel economy and emissions, and a study of the fuel-saving potential of the continuously-variable transmission (CVT) as a replacement for the present-day automatic transmission.

The work covered by this paper includes the design of a demonstration automobile with an Energy Management powerplant utilizing a high-speed energy-storage flywheel, the computer simulation studies used for predicting the fuel economy of flywheel vehicles, and the development of a modeling technique for predicting the transient emissions on a continuous basis of present-day automobiles when driven over any type of driving cycle.

Work to be completed during the current contract year consists primarily of the completion of the demonstration flywheel vehicle and the testing of its fuel consumption and emission characteristics.

## Powerplant with Energy Storage Flywheel

Most of the recent effort of the research program has been directed toward the analysis and design of an automobile with a powerplant incorporating a high-speed energy-storage flywheel.

Computer simulations have indicated that significant fuel savings are possible over the EPA urban driving cycle with this concept. A demonstration vehicle is currently being constructed, based on a 3,000 lb. chassis, to experimentally verify the concept, and to allow experimental data to be obtained that are not currently available.

## Demonstration Vehicle Design

The basic system configuration is given in Fig. 1, and a sketch of the installation in the vehicle by Fig. 2. A relatively stock engine is connected through a clutch to the flywheel package. The engine is to be "turned on" only when the flywheel speed drops below some predetermined value, and shut off when the flywheel reaches maximum design speed. It is to be run only at full throttle to achieve maximum efficiency. The vehicle four-speed manual shift transmission is used in combination with a hydrostatic power-split continuously-variable transmission to allow for proper matching of the flywheel and vehicle speeds under all operating conditions. Some basic features of the flywheel powerplant concept are:

1) Operation of the engine at minimum brake specific fuel consumption.
2) Minimization of nonproductive energy usage.
3) Capability of efficient regenerative braking.
4) Engine calibration for minimum emissions.

The flywheel is being designed and built on a subcontract basis by AiResearch Co. of the Garrett Corporation. The basic configuration is illustrated in Fig. 3. The design principles and components are based partly on previous research sponsored by the U.S. Government. The basic specifications are:

1) A usable energy storage of 2/3 hp-hr.
2) Maximum windage loss of 1 hp.
3) Overspeed protection.
4) Locked bearing protection.
5) Alloy steel construction.
6) 250 ft-lb torque capability.

The continuously-variable transmission, Fig. 4, is being designed and constructed at the University of Wisconsin. It is based on the hydrostatic power-split principle. Most of the power goes through a straight mechanical path, and only part through the hydrostatic path, with the two power components then added together by a gear differential. The hydrostatic transmission (pump and motor) has been obtained as a stock item from Sundstrand. Some of the principle features of the CVT are:

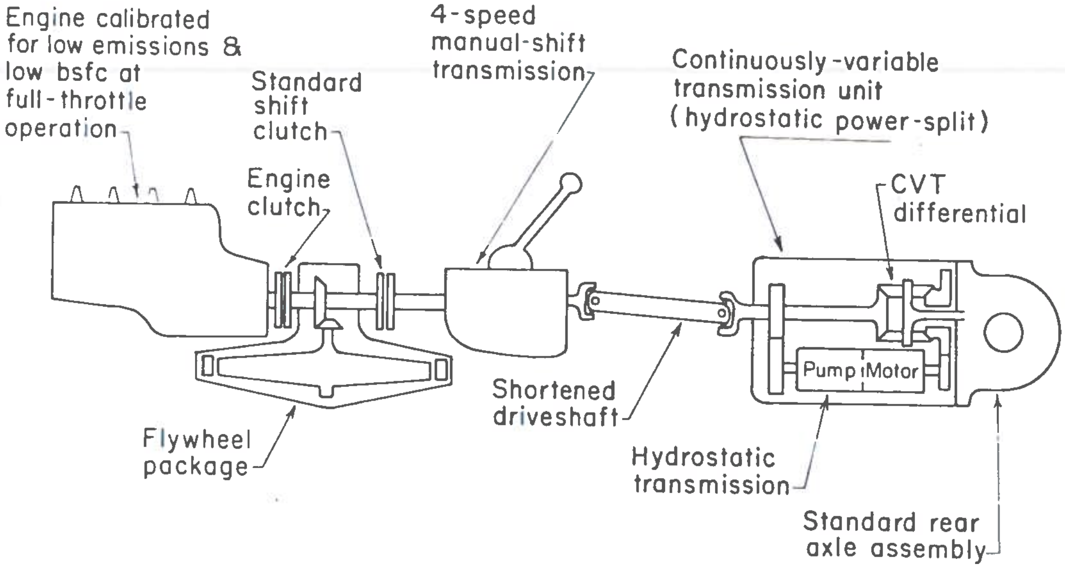

Figure 1. System Configuration

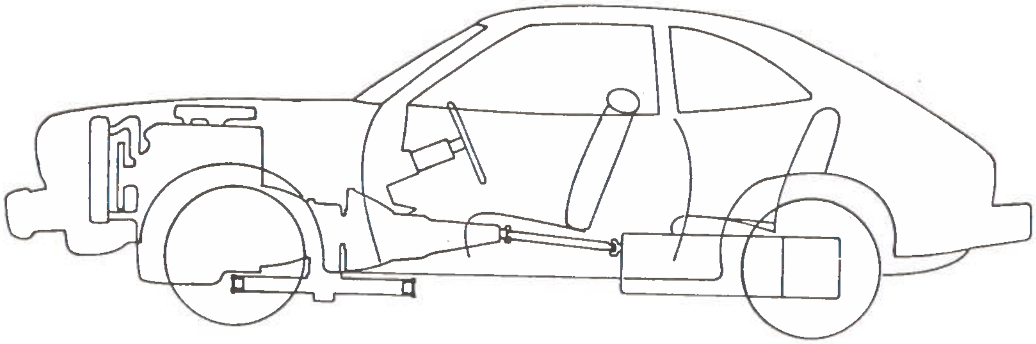

Figure 2. Installation Sketch

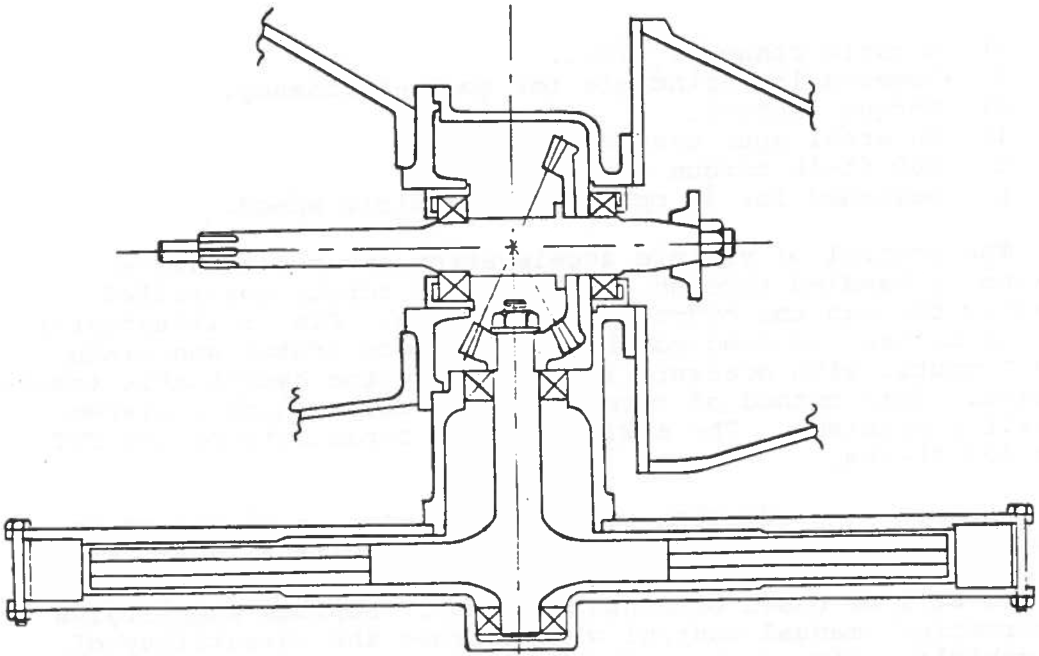

Figure 3. Flywheel Configuration

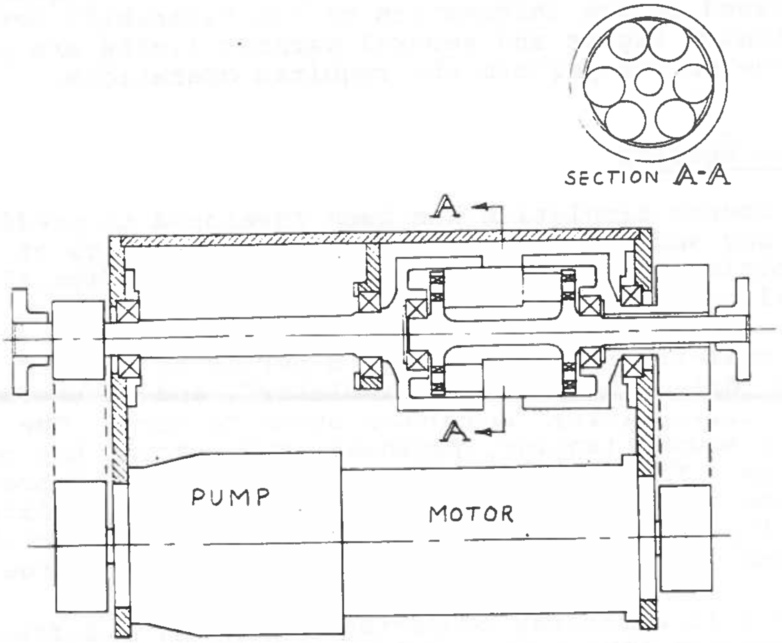

Figure 4. Continuously Variable Transmission Configuration (CVT)

1) A ratio range of 3.5:1.
2) Power-split principle for good efficiency.
3) Torque control.
4) Internal spur gear differential.
5) 400 ft-lb torque capability.
6) Designed for 80 mph maximum vehicle speed.

The control of vehicle acceleration and regenerative braking is handled through the CVT, with torque controlled directly through the hydrostatic pressure. Fig. 5 illustrates how the control is handled through the accelerator and brake pedal inputs, with pressure feedback from the hydrostatic transmission. This method of torque control will minimize system stability problems. The maximum torque capability of the CVT is ± 400 ft-lbs.

Although a production vehicle utilizing an energy-storage flywheel would have automatic controls for virtually all of its required operations, the operation of the demonstration vehicle will be based on manual control. Besides simplifying construction, manual control will improve the versatility of the vehicle. Fig. 6 shows the basic driver compartment controls and instruments. The engine is started and stopped manually with a clutch lever, on the basis of speed information presented by the "flywheel speed - engine start meter". The four speed transmission is shifted the same as that of a standard car, except that the necessary shifting occurs more frequently and must be based on the information of the "gearshift meter". Gear indicator lights and several warning lights are provided to help the driver perform the required operations.

## Simulation Results

A computer simulation has been developed to predict the fuel economy and other performance characteristics of the flywheel vehicle. There are two versions, an all digital program, and a real-time hybrid computer simulation.

The real-time version allows a person to "drive" the vehicle through a "driver compartment simulator", and is useful for the study of "driveability" and other human factors. The simulation of vehicle sounds (engine, flywheel, CVT, etc.), has been included for realism. Fig. 7 shows a set of strip chart recordings from a real-time simulation of a flywheel vehicle being driven over the EPA city driving cycle. For this particular vehicle, the engine came on five times during the cycle to recharge the flywheel.

Table 1 is an energy comparison table for 3 different vehicles:
1) the standard 1976 vehicle with a manual 4-speed transmission,
2) the 1976 flywheel demonstration vehicle now under construction,

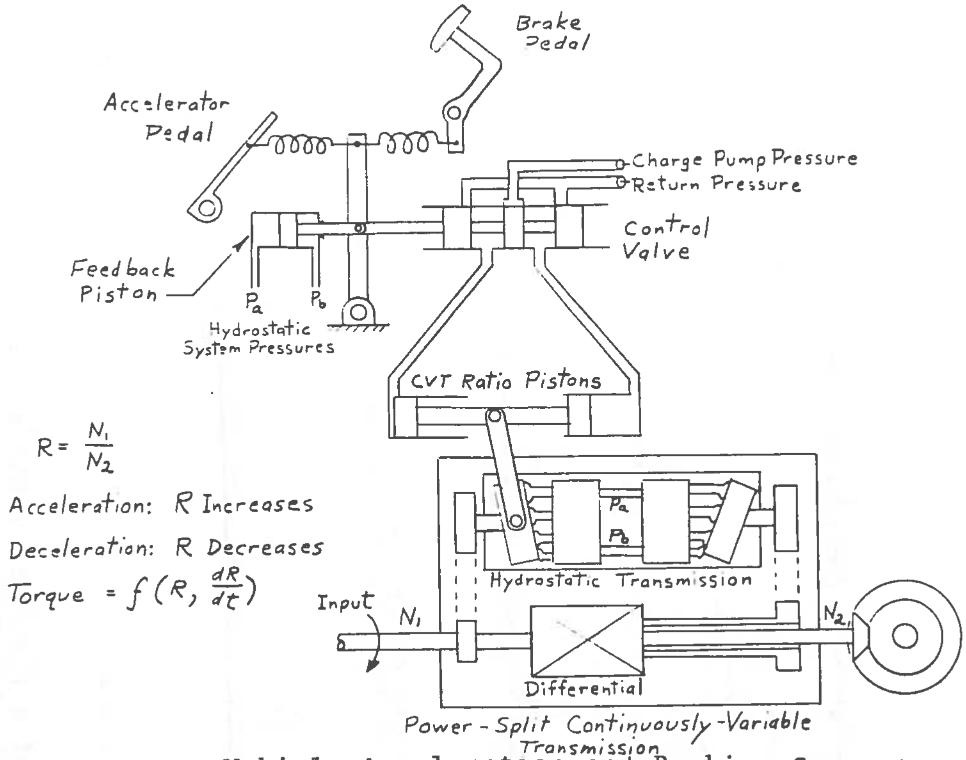

Figure 5. Vehicle Acceleration and Braking Controls

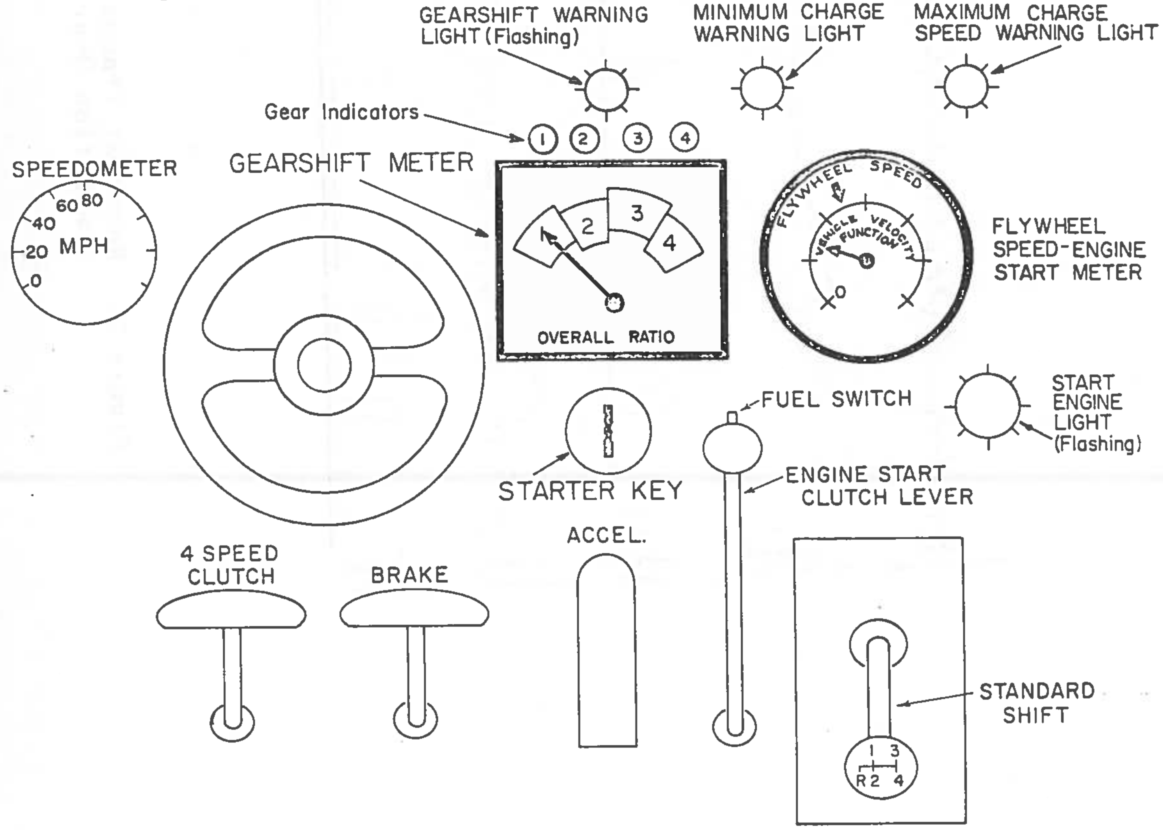

Figure 6. Driver Controls and Instruments

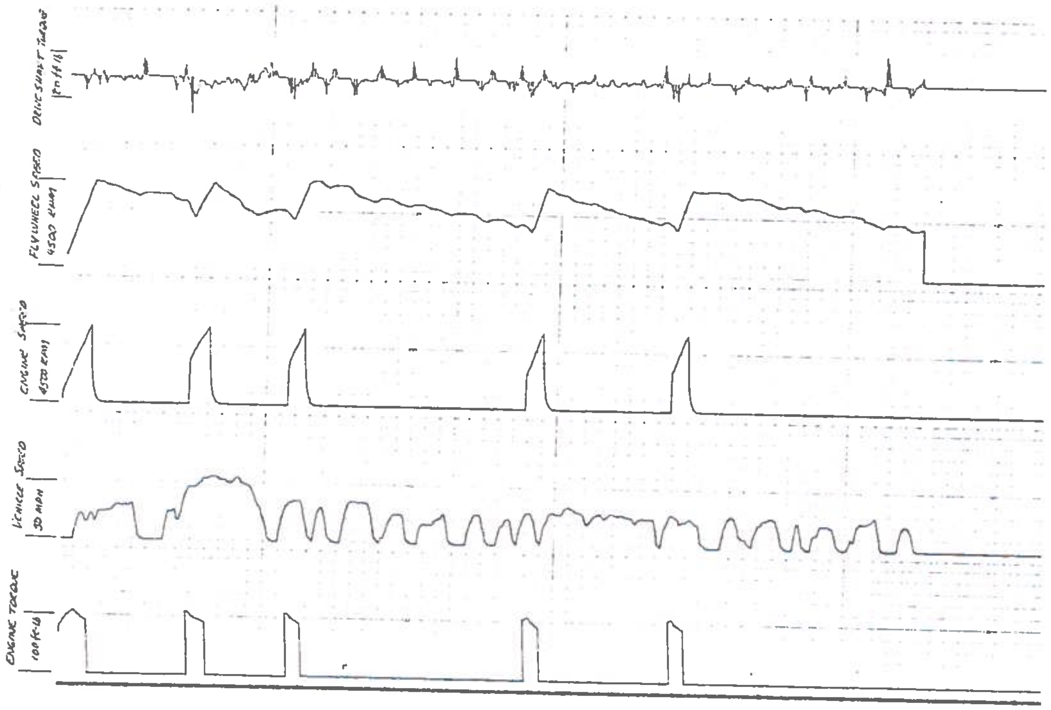

Figure 7. Recorder Traces of a Flywheel Vehicle Simulation Over the EPA-CVS City Driving Cycle

## TABLE 1. EPA-CVS CYCLE ENERGY COMPARISON

| ITEMS | STANDARD 1976 2.3 LITER VEHICLE (HP.SEC.) | | 1976 FLYWHEEL 2.3 LITER VEHICLE (HP.SEC.) | POTENTIAL FROM CONTINUED R & D (HP.SEC.) |
|---|---|---|---|---|
| Road Load | 3700 | | 3702 | 3702 |
| Rear Axle | 470 | | 536 | 536 |
| Transmission | 648 | | 648 | 200* ← |
| | | Flywheel | 855 | 400 ← |
| Deceleration and Brakes | 2555 | CVT | 1809 | 900* ← |
| Total (+) Work | 7373 | FW Gears | 172 | 172 |
| | | Charge Pump | 634 | 100 ← |
| | | Excess Brakes | 50 | 50 |
| Idle & Coast Fuel .25# | ≈ 1111* | Engine Clutch | 99 | 99 |
| | | Engine Inertia | 93 | 93 |
| | | Engine Start | 66 | 66 |
| Total Work | 8484 | | 8664 | 6318 |
| Fuel for (+) Work | 1.655# | | 1.202# | 0.876# |
| Fuel Total | 1.905# | | 1.202# | 0.876# |
| (+) BSFC | 0.808#/HP-HR | | 0.50#/HP-HR | 0.50#/HP-HR |
| Mileage | 24.0 MPG | | 38.0 MPG | 52.0 MPG |
| Improvement | | | 58% | 117% |

*Equivalent Work
Computed at .808#/HP-HR

*A Single CVT
Package Will
Replace Both
Units

and 3) a vehicle with performance characteristics felt to be reasonable as a goal for continued research and development of the concept.

The standard car gets 24 mpg over the EPA city driving cycle. A breakdown of where the energy goes is given in the first column of Table 1. The 1976 flywheel car mileage is predicted to be 38 mpg, an improvement of 58% over the base car. This mileage is based on dynamometer testing at a vehicle weight of 3,000 lbs. The actual vehicle will weigh appreciably more because of the necessity of using commercially available components, but it is felt that the weight penalty of a production design would be small, so that the 3,000 lb. test weight will allow a realistic evaluation of the concept. In looking at the energy losses in the various system components, it is seen that the CVT has the greatest loss, dissipating about half as much energy as is needed to overcome the road load.

The third column is based on an estimate of the improvements that are felt possible with continued research and development. The arrows at the right point to the four components where it is felt that significant improvements in efficiency are feasible, and the energy loss numbers listed are research goals. It should be noted that the combination of a four speed manual shift transmission and a CVT in the 1976 flywheel car would be replaced by a single specially designed transmission in a more advanced vehicle.

The mileage values of Table 1 are based on the 1976 emission standards. Table 2 gives the predicted loss in fuel economy as the emission standards are tightened, for both the standard vehicle and the flywheel vehicle. The predicted economy degradation is seen to be less for the flywheel vehicle.

## Modeling of Transient Emissions

It has been found that the use of steady-state emissions data from engine dynamometer tests is unsatisfactory for predicting the transient emissions over a driving cycle of a vehicle with that engine. Research over the past year has resulted in a new modeling technique that appears to give much more accurate results, although the limited amount of data that has been available for the study makes it difficult to put a quantitative value on the accuracy obtainable.

The new method does not use the steady state data, but instead a set of data, known as Dynamic Average Emissions Flow Tables, obtained from the tabulation and analysis of the continuous emissions data obtained from a vehicle being driven over a driving cycle such as the EPA city cycle. The following is a brief outline of the procedure used in developing a model for a given engine:

Experimentally measured emission flow rates and engine temperatures, available in the form of strip chart recordings, are "lined up" with calculated horsepower values, based on the concept that significant changes in emissions will correspond time-wise to significant changes in engine power. The process of "lining up" the data is done by trial and error, and results in a time displacement (to account for lags in the emissions measuring equipment) and a scale factor (to account for differences in recorder speeds) for each measured variable. Fig. 8 gives an example of such alignment.

The aligned data are then stored on a magnetic tape, with one record for each 0.4 second of the driving cycle. The operating region of the engine is broken up into torque-speed boxes, each covering a range of 10 ft-lb in torque and 100 rpm in speed. Each record on the tape falls into one particular torque-speed box. The average brake specific emission rate for each box is calculated from the points which fall into that box. From these average values, three tables are made, one for each of the three pollutants.

From each of the three Dynamic Average Emissions Flow Tables obtained by the above averaging procedure, a calculated plot of the instantaneous emission flow rate can be generated. The average brake specific flow rate is assumed to occur at the center of each torque-speed box, and flow rates at intermediate points are calculated with four-point interpolation.

Figs. 9 through 14 illustrate the effectiveness of the procedure by comparing the calculated instantaneous emission flow rates over the EPA-CVS city driving cycle with those obtained experimentally. Table 3 compares the total emissions over the cycle obtained by different models with the experimental values. Model I refers to the use of steady-state data from an engine dynamometer. Model II refers to the use of the Dynamic Average Emissions Flow Tables developed from the first 400 seconds of the EPA-CVS cycle, and Model III to the use of the DAEF Tables developed from the total 1372 seconds of the cycle (the same tables as were used for Figs. 9 through 14). Although not perfect, the results of the new technique are much better than can be obtained with the use of steady-state engine data, and the basic approach is much simpler than what we initially thought would be required. An important conclusion of the study is that a single table or map for each of the three pollutants (for a given engine with a given calibration) can

TABLE 2. PERCENTAGE EXPECTED LOSS IN FUEL ECONOMY AS A FUNCTION OF EMISSION STANDARDS

| | Emission Standards gms/mi | 2.3 Liter Standard Manual 24.0 mpg percent loss | 2.3 Liter Hybrid Vehicle 38 mpg percent loss |
|---|---|---|---|
| 1976<br>49 states | HC 1.5<br>CO 1.5<br>NO 3.1 | --- | --- |
| 1977<br>49 states | HC 1.5<br>CO 15<br>NO 2.0 | 4 - 5% | 5 - 10% |
| 1976<br>California | HC .9<br>CO 9.0<br>NO 2.0 | 11 - 12% | 5 - 10% |
| 1977<br>California | HC .4<br>CO 9.0<br>NO 1.5 | 24 - 33% | 10 - 15% |
| 1978 | HC .41<br>CO 3.4<br>NO 0.4 | Unknown | Unknown |

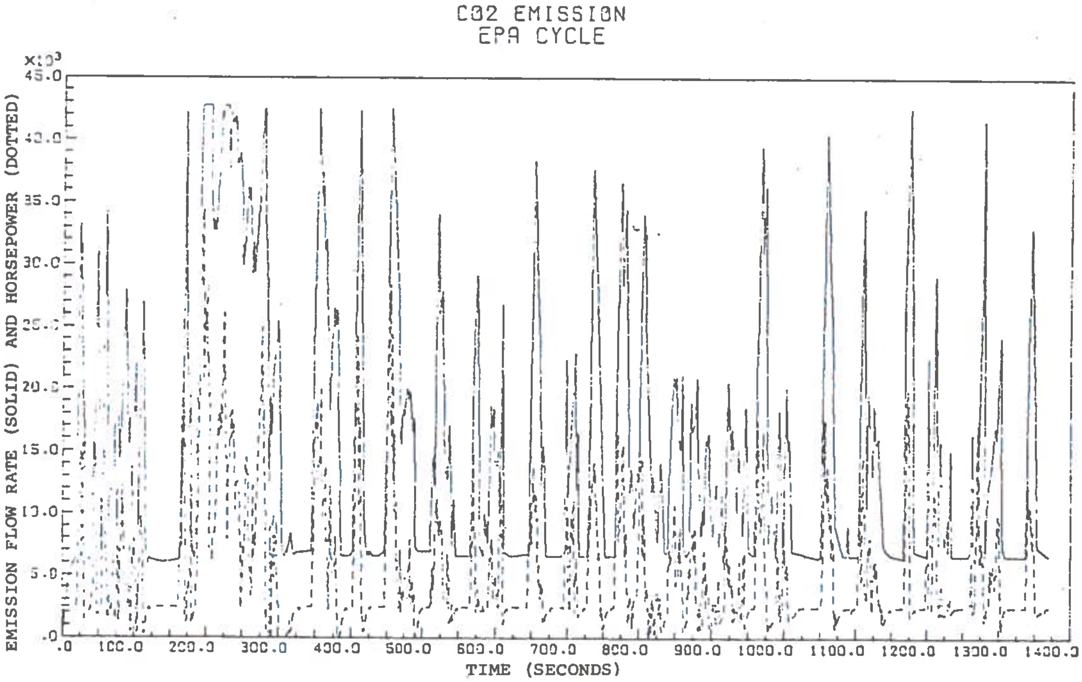

Figure 8. Carbon Dioxide Flow Rate and Horsepower After Data Alignment

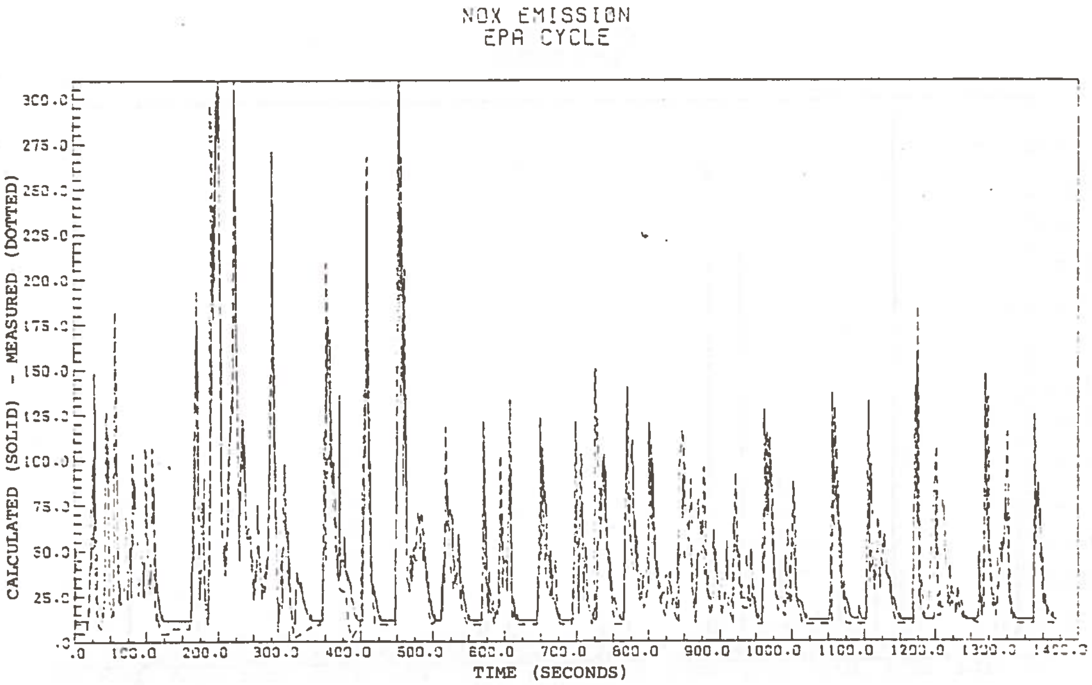

Figure 9. Comparison of Measured $NO_x$ Flow Rate With That Calculated From the Dynamic Average Emissions Flow Table

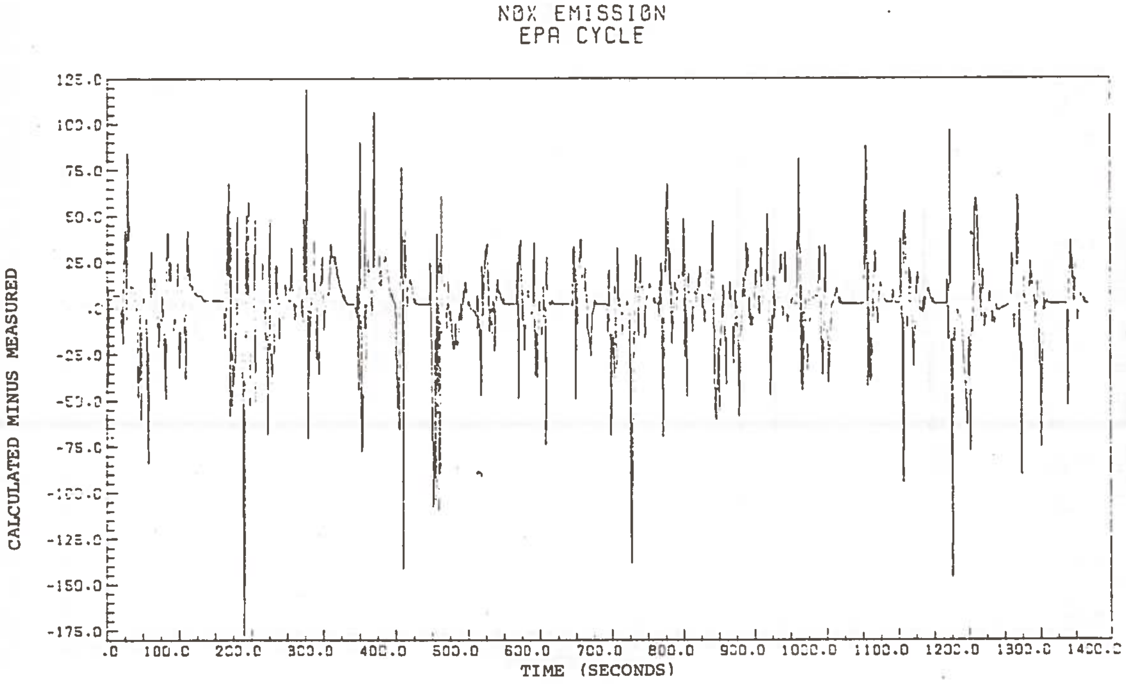

Figure 10. Error Between Measured $NO_x$ Flow Rate and That Calculated From DAEFT

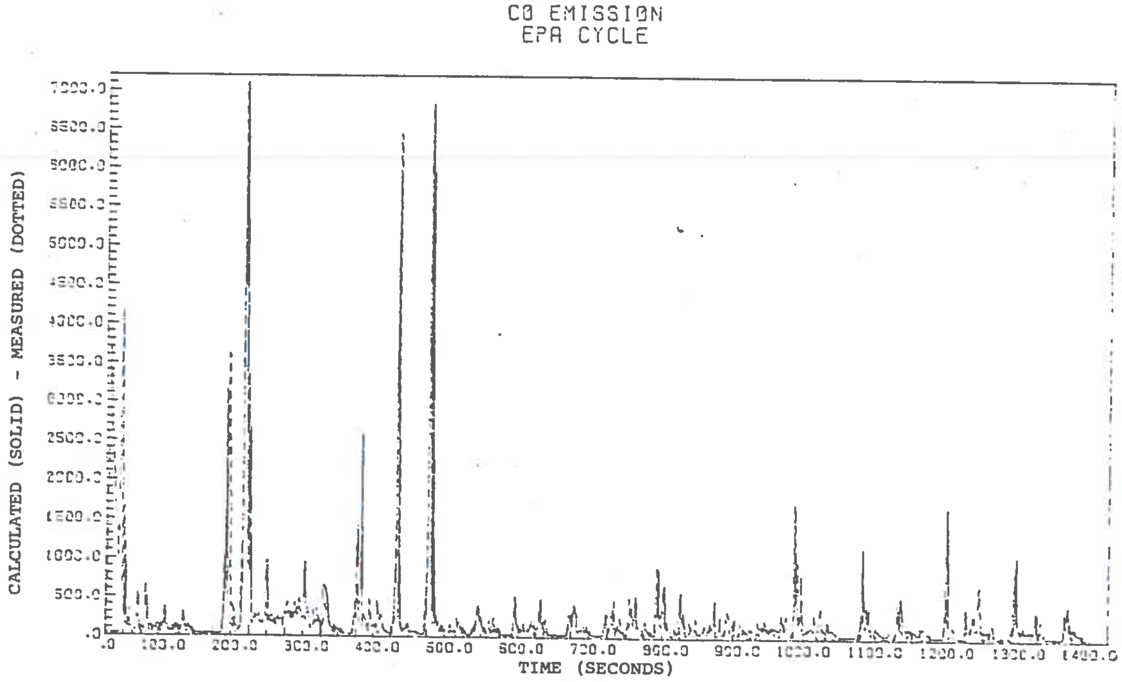

Figure 11. Comparison of Measured CO Flow Rate With That Calculated From DAEFT

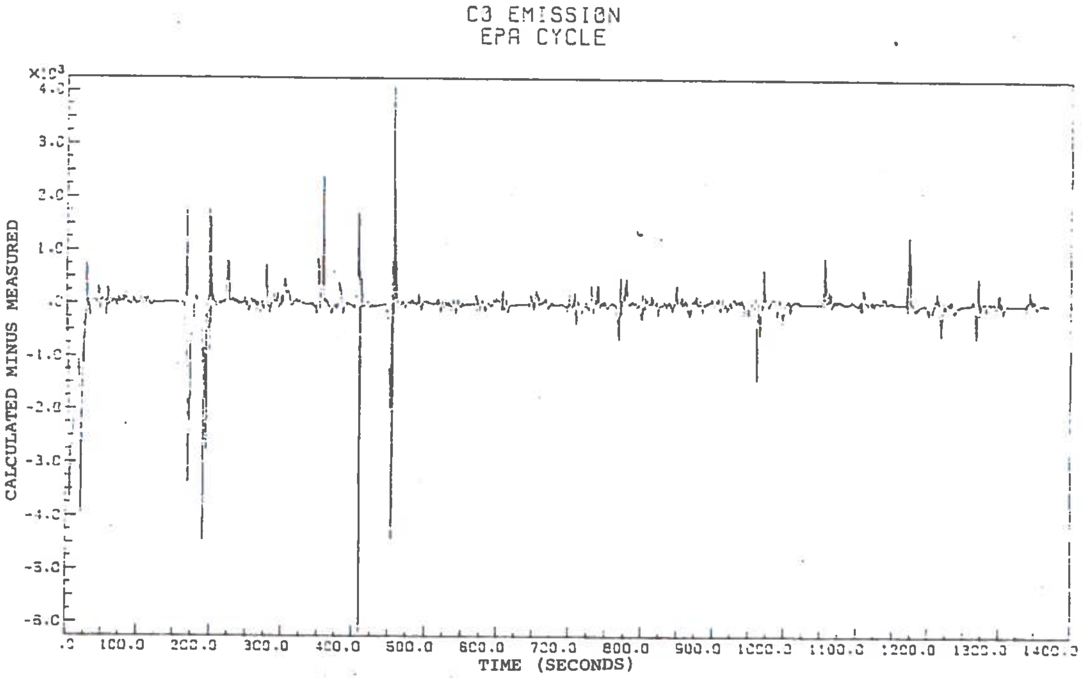

Figure 12. Error Between Measured CO Flow Rate and That Calculated From DAEFT

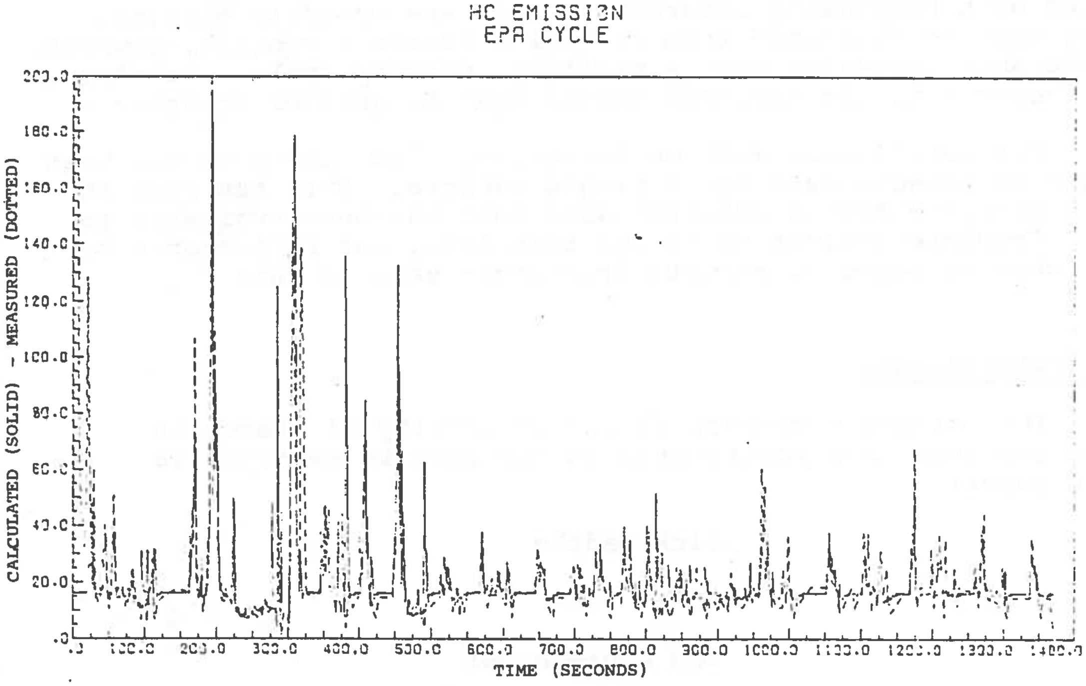

Figure 13. Comparison of Measured HC Flow Rate With That Calculated From DAEFT

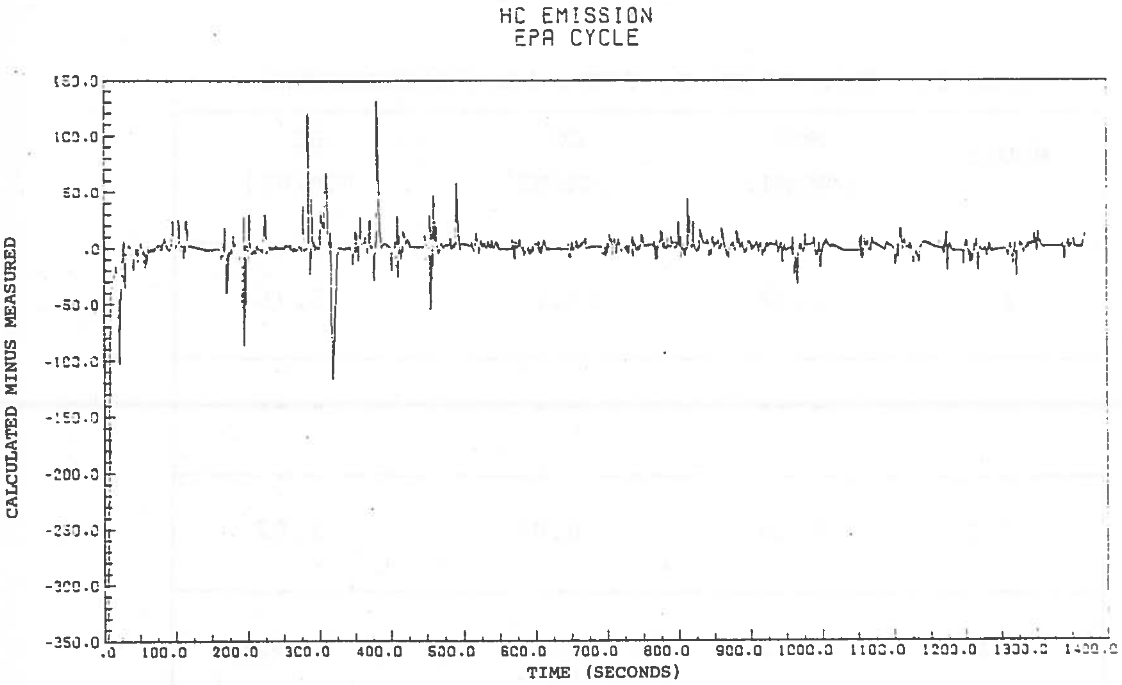

Figure 14. Error Between Measured HC Flow Rate and That Calculated From DAEFT

be satisfactorily used to predict instantaneous emission flow rates with reasonable accuracy if they are properly obtained. They must be developed from an engine inside a vehicle, however, preferably operating over a realistic driving cycle. Further refinements to the approach should lead to greater accuracy.

Our conclusions must be tentative, since the work has been based on EPA-CVS data for a single vehicle. This has been the only complete set of coherent data that has been available to us. Complete evaluation of the technique, and refinements to it, must be based on results from other sets of data.

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Peter Ting

Tom Hausenbauer

Doug Brooks

TABLE 3. COMPARISON TO TOTAL FLOW PREDICTIONS

| MODEL | NOX (GM/MI) | CO (GM/MI) | HC (GM/MI) |
|---|---|---|---|
| I | 2.24 | 19.1 | 1.76 |
| II | 2.05 | 9.2 | 1.16 |
| III | 2.14 | 10.07 | 1.02 |
| ACTUAL | 2.02 | 9.3 | .91 |

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