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INCREASED FUEL ECONOMY IN TRANSPORTATION SYSTEMS BY USE OF ENERGY MANAGEMENT THIRD YEAR'S PROGRAM

MASTER

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16. Abstract <p>The report covers the results accomplished during the third year of a three-year research program, the overall goal of which has been to conceive and evaluate practical ways to increase automobile fuel economy by energy management within the engine-transmission-vehicle system. The third year was devoted primarily to the detailed design, construction, and preliminary evaluation of a Flywheel Energy Management Powerplant (FEMP) installed in a Pinto. The vehicle has been built to experimentally verify performance simulations and to allow the practical aspects of a real flywheel vehicle to be studied.</p> <p>The FEMP consists basically of an internal combustion engine, a high-speed energy-storage flywheel, and a hydrostatic power-split continuously-variable transmission (CVT) system. The flywheel drives the car, and the engine comes on to "recharge" it (with efficient wide-open throttle operation) only when the flywheel speed drops below a predetermined value. The concept also permits effective and efficient regenerative braking.</p> <p>Computer simulations have indicated an improvement in city fuel mileage of about 50%, with improvements of 100% appearing feasible with further research. Preliminary testing of the car shows favorable performance.</p>			
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INCREASED FUEL ECONOMY IN TRANSPORTATION
SYSTEMS BY USE OF ENERGY MANAGEMENT-
THIRD YEAR'S PROGRAM

Executive Summary

Introduction

This report covers the third year of a three-year research program, the principal objective of which has been to conceive and evaluate practical ways to increase automobile fuel economy by energy management within the engine-transmission-vehicle system. The first year was devoted primarily to the development of computer simulation techniques for evaluating performance of standard automobiles and automotive components. During the second year, the computer simulation techniques were expanded to allow simulation of unorthodox energy management powerplant system concepts, in particular, powerplant systems incorporating an energy-storage flywheel. With the aid of the computer simulations, a preliminary mechanical design was evolved that showed the potential of a significant improvement in fuel economy.

The third year's effort, to which this report is dedicated, has consisted primarily of the detailed design, construction, and preliminary testing and evaluation of a Flywheel Energy Management Powerplant (FEMP) installed in a Ford Pinto. The purpose of the research vehicle is to experimentally verify performance simulations and to allow the practical aspects of a real flywheel vehicle to be studied.

A schematic diagram of the powerplant system is given by Fig. 1. A sketch of its location in the Pinto chassis is given by Fig. 2, while Figs. 3, 4, and 5 are photographs of the actual installation. It should be noted that the research powerplant has been constructed under a tight time schedule and with limited funds, with the design based largely on "off-the-shelf" components, so that the resulting design is not meant to resemble

Fig. 1 Configuration of Pinto Flywheel Energy Management Powerplant (FEMP) System

Fig. 2 Location of the Flywheel Energy Management Powerplant (FEMP) in the Pinto chassis

Fig. 3 Installation of the flywheel package in the Pinto

Fig. 4 Installation of the continuously-variable transmission in the Pinto

Fig. 5 The Pinto with the Flywheel Energy Management Powerplant

in size and weight what could be accomplished in a production vehicle.

The car can be considered to be driven by the flywheel. When the flywheel speed drops below some predetermined "minimum" value, the engine is clutched in and recharges it at efficient wide-open throttle operation. The continuously-variable transmission (CVT) is required to continuously match the flywheel and vehicle speeds under all conditions. The concept allows efficient regenerative braking, the flywheel speeding up as it absorbs the kinetic energy of the decelerating vehicle.

Preliminary Evaluation of the Flywheel Vehicle

The flywheel research vehicle has been completed and driven. In general, the results have been very satisfactory. Preliminary tests have enabled us to make the following tentative statements about the system, its operating characteristics, and the problems which are evident at this point.

- The torque control system used seems quite satisfactory. Good positive control is achieved, with virtually no tendency toward any surging or other instability on acceleration, regenerative braking, or steady-speed cruise. It is felt that the torque control principle is sound, with only minor modifications being required to have a system that would be satisfactory for a production vehicle.
- Regenerative braking is practical and effective. No significant practical problems have been found with the application of regenerative braking, except for the limitations of wheel slippage. In this regard, a front wheel drive system would allow about twice the rate of deceleration while still employing regenerative braking alone.

- The on-off method of engine control has been found to be a satisfactory technique for improving average engine efficiency. A significant problem, however, is the high noise level obtained. This is particularly noticeable at low vehicle speed when the noise of an engine running at wide-open throttle and a relatively high rpm is not normally expected. If the flywheel concept proves viable, however, it is felt that modern noise-abatement techniques and an engine design for this purpose should reduce the noise level to a satisfactory level.
- The noise level of the hydrostatic components in the continuously-variable transmission is somewhat higher than would be desirable for a production vehicle. This is particularly true because of the distinctive and unfamiliar hydraulic sounds. Great strides are currently being made in reducing hydraulic noise generation, so that it is felt that this noise problem can be controlled. It should also be remembered that further research may show that a non-hydrostatic type of CVT may be better for the flywheel vehicle application.
- There is currently considerable noise from the spiral-bevel gear pair in the flywheel package because of a "dry sump" lube system. Again, it is felt that modern noise abatement techniques would reduce this to an acceptable level in a production design.

Although precise fuel consumption testing has not been completed, the preliminary testing that has been done indicates that the flywheel power-plant does provide a significant improvement in fuel economy over the standard vehicle.

FEMP Vehicle Design Details

The engine is basically the stock Pinto 4-cylinder 2.3 liter engine, modified for us by Ford Motor Company to allow fuel-efficient operation with low emissions at wide-open throttle conditions. Modifications include an electronic fuel injection system, a special EGR (exhaust gas recirculation) system, and a modified spark advance curve.

The flywheel package was built to our specifications by AiResearch Manufacturing Company, a division of Garrett Corporation. It utilizes a 23 inch diameter wheel in an evacuated housing, with a specified maximum no-load friction loss of 1 hp at its maximum design speed of 10,000 rpm. It will store 0.75 HP-HRS (0.5 KW-HRS).

There are two clutches used: one between the engine and flywheel package, and one between the flywheel and transmission. These are both stock Pinto units.

The system's transmission consists of two components: the stock 4-speed Pinto gearbox, and a continuously-variable transmission (CVT) designed and constructed specifically for this project. The two transmission components are used in lieu of a single integrated package for the following reasons:

- "Off-the-shelf" components are able to be utilized, allowing early and economic construction.
- The ratio range requirement of the CVT is reduced, which allows its average efficiency to increase.
- The hydrostatic components rotate at the lowest possible speed for any driving condition, reducing their friction losses.

Component Testing and Evaluation

A considerable amount of testing has been done on the various components of the FEMP system. The results have been used in the computer simulations to develop a more up-to-date prediction of the vehicle fuel economy.

Engine Tests A number of tests were run on a chassis dynamometer at the Ford Motor Company to obtain the engine emissions and fuel consumption characteristics at various calibration settings. This was done with the modified engine in the otherwise stock Pinto. These data were obtained for the most part by accelerating the Pinto in 2nd gear under wide-open-throttle conditions with a high simulated inertia and road load from 20 to 50 mph. The pertinent engine performance and emissions data were recorded on a continuous basis during these runs. The reduced data indicate that an average BSFC of 0.5-lb./bhp-hr should be obtainable from the engine with the on-off operating procedure while meeting the current 1977 emissions standards without a catalytic converter.

Hydraulic Pump and Motor Tests Dynamometer tests have been run on the hydrostatic pump and motor used in the continuously variable transmission, covering the full range of expected operation. Losses were found to be somewhat higher than expected, particularly under conditions of small pump stroke, conditions in which the efficiency is not normally of much concern when the units are used in more orthodox applications.

Flywheel "Spin-Losses" Friction tests on the flywheel package were conducted by AiResearch before shipping it to us. The spin-loss (friction loss with no power being supplied to or taken from the assembly) was found to be within specifications, less than 1 horsepower (including the electrical power required to drive the lubrication-vacuum pump) at the full design speed of 10,000 rpm. This friction value was obtained by a "coast-down"

test, in which the flywheel was first spun up to its maximum design speed, and then disconnected from the driving device and allowed to coast freely. By recording speed at frequent intervals of time during the coast-down, spin-loss could be readily determined as a function of speed.

Spin-losses of other drivetrain components were also measured by the "coast-down" technique. The following tests have been performed:

- flywheel with the engine clutch only installed
- flywheel with both clutches installed
- flywheel, clutches, and 4-speed transmission (data being obtained for all 4 gear ratios)
- the flywheel, clutches, 4-speed transmission, CVT, and complete rear axle assembly (with wheels off the ground and brake drums removed).

The spin losses of the flywheel package and four-speed gearbox were found essentially equal to the originally assumed values (ATF was substituted for gearbox oil). The two clutches and the CVT (in their current status) show spin losses considerably higher than originally calculated.

Performance Predictions

The experimental component data have made it possible to obtain an up-to-date prediction of fuel economy. Based on the measured characteristics of all components as currently installed in the Pinto, approximately 28 mpg over the EPA-CVS city driving cycle has been predicted by computer simulation. Future adjustments and modifications should raise this figure about 20%.

Preliminary Chassis Dynamometer Tests

EPA-CVS city driving cycle runs were conducted at Ford Motor Company in August, 1976. Although a malfunction of the fuel injection system prevented valid fuel consumption and emission figures from being obtained, the tests did produce the following information:

- The flywheel system has adequate ruggedness for repeated driving of the EPA-CVS cycle
- The system characteristics (and in particular the torque control) permit professional drivers to readily follow the EPA-CVS schedule
- The number of charge cycles over the EPA-CVS cycle was essentially the same as predicted by computer simulation.

Plans for Additional Vehicle Tests

With the Pinto FEMP vehicle operational, it is planned to run a complete series of tests to determine not only its fuel economy and emissions characteristics, but also to determine insofar as possible the relative effect of each system component and its characteristics on the fuel consumption and emissions. This will serve to verify our computer simulation techniques and may serve as a guide to modification of the computer program.

A chassis dynamometer is being installed at the University of Wisconsin. With the development of an accurate fuel flow meter, it will be possible to run fuel consumption tests over the EPA city and suburban cycles, as well as at constant speeds. It may not, however, be possible to obtain emissions data on the U.W. dynamometer.

This will depend on the feasibility of developing the required emissions measuring equipment.

In order to obtain emissions and fuel economy data in a standard EPA test, it may be necessary to take the car to a completely instrumented industrial facility or to the EPA test facility in Ann Arbor, Michigan. The testing done beforehand on the U.W. dynamometer will be very useful in preparing for the complete tests, however, because variations in operating procedures and adjustments to system components will have been made.

Future Flywheel Vehicle Research

The testing program for the Pinto FEMP vehicle, in combination with the testing of the individual components that has already been accomplished and which will be continued during the coming year, will provide a much clearer view of the true potentials and problems of the flywheel concept. This understanding should enable us to clearly define and specify the performance characteristics required of each system component if a viable flywheel vehicle is to be obtained.

The work to date has already pinpointed the transmission (CVT) as the most critical element in terms of efficiency. In our program for the coming year, we therefore plan to place a concentrated effort on CVT's, investigating a number of alternative principles such as traction drives, hydrostatic and hydrostatic power-split transmissions, electric and electric power-split transmissions, and a multi-speed gear box in combination with a controllable type of torque converter.

It is expected that a combination of theoretical analysis, design ingenuity, component testing, and testing of the flywheel research vehicle should allow determination of the practical potential of the flywheel powerplant concept within three or four years.

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The Mechanical Engineering Machine Shop at the University of Wisconsin handled most of the machining and assembly of the continuously-variable transmission.

The Engineering Experiment Station of the University of Wisconsin has helped with the administration and bookkeeping aspects of the contract.

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1.0 INTRODUCTION

1.1 Objectives and Summary of Program

The basic goal of the three-year research program has been to study and evaluate the fuel-saving potential of hybrid motor vehicle powerplant systems falling in the category of "Propulsion Energy Management Systems". This term is used to refer to system configurations consisting of a prime mover, an energy storage device, a transmission, and the necessary controls.

The first year of the program was devoted primarily to the development of computer simulation techniques and programs (with complete documentation) which would allow the accurate prediction of the performance and efficiency characteristics of all the significant components of an automobile, as well as the total vehicle system, on a continuous basis, covering the total range of operating conditions. These programs were based, insofar as possible, on experimental data obtained from major automobile manufacturers. The detailed simulation techniques allow not only the accurate prediction of fuel economy over any driving cycle, but also the determination of the effects produced by changes in any of the system components. Both all-digital and hybrid computer real-time versions of the program were developed. A "driver compartment simulator", allowing a person to "drive" the vehicle in real time, was built for use with the real-time program. The first year's work also included a study of the potential improvement in fuel mileage obtainable with the use of a continuously-variable transmission (CVT) and an algorithm that would allow it to be used in an optimal manner under all types of driving conditions. Preliminary studies of Propulsion Energy Management Systems during the first year led to the decision to further pursue the study of systems utilizing a high-speed energy-storage flywheel because of their potential for significant fuel savings in city driving. For details of the first year's work, the reader should refer to [1,2,3]*.

* Numbers in brackets designate references at the end of the report.

During the second year of the research program, the main emphasis was on the simulation and evaluation of systems containing a high-speed energy-storage flywheel. Simulations were done not only with the all-digital program, but also with the hybrid computer real-time version using the driver compartment simulator in order to study and evaluate the driveability and other human factors so important in an unorthodox vehicle of this type. Based on the simulations, a preliminary design was developed to serve as the basis of an experimental research vehicle to be constructed the 3rd year. In addition to the main work on the flywheel vehicle, work was done on the development of computer modeling techniques to accurately simulate the emissions of an internal combustion engine automobile on a continuous basis under transient conditions. Also, the computer simulation programs developed in the first year were used to study the effects on fuel economy and emissions of relatively straightforward changes to present-day drivetrain components (transmissions, torque converters, rear axles, etc.). For details of the second year's work, the reader should refer to [4,5,6].

1.2 Work Accomplished During the Third Year

The third year of the research effort, to which this report is dedicated, has been devoted to the job of designing, building, and performing preliminary tests on a research flywheel vehicle (based on the Ford Pinto) for experimental evaluation of the flywheel energy management concept. The major tasks involved in this program have been:

- The development of detailed specifications for all components of the flywheel vehicle.
- The letting of a subcontract (to AiResearch Manufacturing Company) based on competitive bidding for the design and construction of the energy-storage flywheel package to our specifications.

- The detailed design and construction (at the University of Wisconsin) of a hydrostatic power-split transmission based on commercially available hydraulic components (Series 20 pump and motor manufactured by Sundstrand Corporation).
- Special calibration of the stock Pinto engine (with assistance from Ford Motor Company) to allow good fuel economy with satisfactory emissions characteristics when operated in an on-off manner at wide-open throttle.
- Testing of the various system components to see if they meet the original specifications, and the revision of fuel mileage predictions based on the measured component efficiency data.
- The installation of the flywheel power-plant system in the Pinto chassis, with the extensive chassis modifications required.
- Preliminary testing of the assembled vehicle to determine its driving characteristics, control system stability, and other significant characteristics of the basic concept and the specific design used.

1.3 Future Work

Although the three-year research program covered by this report and the two previous ones [1,4] has ended, research will be continued at the University of Wisconsin on the flywheel power-plant concept. The follow-on programs are being supported by the U.S. Department of Transportation Office of University Research, and the Urban Mass Transit Administration. Details are given in Chapter 7 of this report.

2.0 FLYWHEEL ENERGY MANAGEMENT POWERPLANT (FEMP) DESIGN

2.1 Introduction

The preliminary design of the FEMP system was completed during the second year of the research program, and the resulting configuration is given by Fig. 2-1. During the third year it was necessary to consider all the mechanical and electronic details of the actual system to be constructed, and also the chassis modifications required to install it in the Pinto. This chapter outlines the basic system design features, including the system controls, and the chassis installation. The design details of the individual components are covered in succeeding chapters.

2.2 FEMP Configuration

The basic FEMP (Flywheel Energy Management Powerplant) system (Fig. 2-1) consists of three basic components:

- The Pinto internal combustion engine (modified)
- The flywheel package, with a stock Pinto clutch at both the input and output shafts
- A transmission system consisting of a stock Pinto 4-speed manual transmission and a specially designed and constructed hydrostatic power-split continuously-variable transmission (CVT).

To explain the method of operation, it is convenient to consider the vehicle as always powered by the flywheel. The engine is used to "recharge" the flywheel (running under wide-open throttle conditions) whenever the speed of the flywheel drops below some predetermined value. When the engine runs energy goes to both driving the vehicle and

Fig. 2.1 Configuration of Pinto Flywheel Energy Management Powerplant (FEMP) System

charging the flywheel. This configuration can be termed "parallel drive". At all other times the engine is completely shut down; i.e., there is no idling operation. The CVT is required to continuously match the flywheel and vehicle speeds under all conditions, since both speeds are constantly varying with no specific relationship between them. The reason for the 4-speed gearbox is to allow a simplified and more efficient CVT design, while still allowing the speed ratio range versatility required by the system. The system allows effective and efficient regenerative braking, with the braking energy returned to the flywheel as kinetic energy by speeding it up.

The research vehicle is not meant to be considered in the same category as a prototype. The design details were chosen largely on the basis of what could be built and assembled within a one-year program, limiting us in most instances to "off-the-shelf" components. The design details and components were chosen with efficiency and availability as the primary considerations, and as a result, size and weight have generally suffered.

2.3 System Controls

The basic system control concepts have not changed appreciably over the past year. Figure 2.2 shows the positions of the basic driver controls and instruments. The major instruments and controls added because of the FEMP system, and a brief summary of their significance are

- The engine start clutch and fuel switch - when the engine speed drops to or below its minimum permissible value (a function of vehicle speed) the engine clutch is engaged manually by means of the engine start clutch lever. Immediately upon engagement the fuel switch must be turned on. When the flywheel speed reaches the maximum allowable value, the engine clutch must be released and the fuel switch simultaneously turned off.

Fig. 2.2 Basic driver controls and instrumentation for the FEMP Pinto

- The gearshift meter - the gearshift meter tells the driver at all times which gear he should be in for maximum fuel economy. Its reading is based on the ratio between the flywheel and driveshaft speeds. The position of the gearshift lever indicates to the driver the gear he is actually in.
- The Flywheel Speed - Engine Start Meter - there are two needles on this meter. One indicates directly the speed of the flywheel in rpm. The other indicates the "vehicle velocity function", i.e., the minimum speed the flywheel should be allowed to run corresponding to the instantaneous vehicle speed, and therefore varies with vehicle speed. This meter indicates to the driver when he will need to start the engine to recharge the flywheel. The meter readings are based on two digital counter systems that measure the required speeds, and an electronic comparison circuit.

The driving of the car (i.e., acceleration and deceleration) is accomplished by means of a torque control system. The accelerator and brake pedals command torque (positive and negative, respectively). A direct mechanical linkage connects the two pedals to a valve which controls the hydraulic pressure in the hydrostatic pump and motor assembly within the CVT. The torque output of the CVT is directly proportional to the torque of the hydrostatic pump, which in turn is directly proportional to the hydraulic pressure.

In order to convert pedal motion (accelerator and brake) to hydraulic pressure, a special valve is required. The valve chosen is the newly available "Variable Pressure Control Valve" manufactured by Sundstrand. It has been designed to mount directly on the Series 20 pump we are using (replacing the ratio control valve normally used), and causes the hydraulic system pressure to be directly proportional to the angular position of a simple lever. A positive movement produces positive pressure (vehicle

acceleration), and vice-versa.

The preliminary testing accomplished to date indicates that the "Variable Pressure Control Valve" has almost exactly the type of operating characteristics desirable for control of the flywheel vehicle. A schematic diagram of the valve is given by Fig. 2.3.

The torque control system was chosen and designed on the basis of computer simulations which demonstrated that the alternative approach, ratio control, would tend to cause serious stability problems for a flywheel vehicle, while torque control if properly implemented should be inherently stable.

2.4 Installation in the Pinto Chassis

The FEMP installation has required a considerable amount of chassis modification. These changes have been necessitated primarily because of the large sizes of the flywheel package and the CVT. Figures 2.4 and 2.5 show the location of the FEMP components relative to the Pinto body and the original frame members.

In order to install the flywheel, it was necessary to (1) cut out a section of the main front cross-member, welding in a new piece to box it in again and restore it to approximately its original strength, (2) relocate the front suspension control rods, attaching them to new mounting brackets in front of the A-frames rather than behind them, (3) remove the original side frame members, replacing them with new structural members that clear the flywheel package, (4) remove most of the floorboard (which also would interfere with the CVT). In order to achieve adequate frame strength, additional structure has been added in the general area of the flywheel. The flywheel package is attached to the frame by means of four rubber engine-type mounts. The original two engine mounts are retained for the Pinto engine, with a slight relocation. The engine, flywheel package, two bell housings, two clutches, and the four-speed gearbox form a rigid unit located by the six flexible mounts. Figures 2.6, 2.7, and 2.8 show the details of the actual installation.

Fig. 2.3 Schematic diagram of the Sundstrand "Variable Pressure Control Valve" used for torque control

Fig. 2.4 Location of the Flywheel Energy Management Powerplant (FEMP) in the Pinto chassis

Fig. 2.5 Location of the flywheel package with respect to original Pinto frame members

At the rear end of the vehicle, the CVT and rear axle differential have been bolted rigidly together to form a single unit which is fastened to the frame by means of four rubber engine-type mounts. This arrangement (which allows the CVT and differential mass to be sprung) has been made possible by replacing the Pinto rear axle by a Corvair independent rear suspension system. Further modifications were required to allow fastening the Corvair wheel hubs to the Pinto springs, and to attach arms to control the rear wheel toe-in. Two new cross-frame members had to be installed for mounting the CVT and the Corvair differential. Figures 2.9, 2.10, and 2.11 show the details of this part of the installation.

Other significant installation tasks that have had to be performed include

- installation of the engine clutch lever, and two modified clutch cable systems.
- Design and installation of the mechanical linkage between the accelerator and brake pedals and the Variable Pressure Control Valve.
- Construction of a shortened driveshaft.
- Relocation of the front seats to allow clearance for the CVT.
- Construction of a cover for the CVT to improve sound attenuation.

Fig. 2.6 Installation of the flywheel package in the Pinto - view from the left

Fig. 2.7 Installation of the flywheel package in the Pinto - view from the right

Fig. 2.8 View through the right front fender well showing the mounted flywheel and the re-located front suspension control rods

Fig. 2.9 Installation of the continuously-variable transmission in the Pinto

Fig. 2.10 View from the rear showing the installation of the Corvair rear axle assembly in the Pinto

Fig. 2.11 View through the left rear fender well showing the installation of the Corvair rear axle assembly

3.0 FLYWHEEL DESIGN DETAILS

3.1 Introduction

The flywheel package was designed and built to our specifications by AiResearch Manufacturing Company of California, a Division of the Garrett Corporation. A report has been supplied to us by AiResearch [7] covering the design details and calculations for the unit, as well as an assembly drawing of the total package. The information in this section is based primarily on the AiResearch report.

3.2 Design Details

Table 3.1 summarizes the basic design requirements, while Table 3.2 gives the features of the finished product. The flywheel package (Figs. 3.1 and 3.2) consists basically of the energy storage flywheel itself, a pair of helical bevel gears with a 2:1 reduction ratio to transmit energy to and from the flywheel, a lubrication and vacuum system, and the case structure which includes a safety shield system.

The flywheel itself is composed of four steel discs of uniform thickness mounted on a central steel shaft. In order to stay within the budget constraints of the program, the flywheel design was based on using the same basic flywheel disc configuration as used on the Advanced Concept Train (ACT I) energy storage unit. The steel discs are identical (same part number) to the ACT-I discs, the shaft is of the same material, and the same interference fit is used. Thus the analytical analysis and experimental testing done earlier at AiResearch was directly applicable.

The flywheel design incorporates a speed-limiting system developed by AiResearch. The proper shrink fit ensures retention of the discs to the shaft up to a speed of 11,550 rpm. If the shaft should be rotated at a higher speed, the discs would loosen, so that the discs themselves would not rotate at the higher speed.

Table 3.1

SUMMARY OF FLYWHEEL DESIGN REQUIREMENTS

Maximum input shaft design speed	5,000 rpm
Energy storage between 100% and 30% rpm	0.66 hp-hr
Proof test speed	110% rated*
Self-limiting speed	115% rated
Containment speed	115% rated
Design "burst" speed, minimum	135% rated
Maximum input/output shaft torque	250 ft-lbs
No load power losses, maximum	1.0 hp
Operating ambient temperature	0 to 100° F
Operating altitude	0 to 10,000 ft
Weight	343 lbs

*Rated speed for the design herein described is 10,000 rpm.

Table 3.2

SUMMARY OF FLYWHEEL PACKAGE FEATURES

Input shaft rated 100% speed	5,000 rpm
Flywheel shaft rated 100% speed	10,000 rpm
Gear ratio	2:1
Flywheel polar moment of inertia	2.68 ft-lb-sec ²
Flywheel energy storage at 100% speed	1.47 x 10 ⁶ ft-lb
	0.742 hp-hr
Available energy 100% to 30% speed	1.37 x 10 ⁶ ft-lb
	0.675 hp-hr
Weight (dry)	500 lbs

Fig. 3.1 Assembly drawing of the flywheel package

Fig. 3.2 The flywheel package, showing oil reservoir, starter motor, and rear bell housing

A steel containment ring, based on ACT-I analyses and test results, is provided at the periphery of the flywheel to ensure containment of all radial-directed fragments in the extremely unlikely event of a flywheel disc failure. To ensure containment of axially-directed fragments (which would have much less energy than those directed radially), the upper plate is steel and the lower flywheel cover is made with 1/2" thick aluminum.

To prevent the possibility of the total vehicle rotating upon the roadway if there were a sudden seizure between the flywheel and the case, the flywheel housing is mounted on the bearing support housing in a manner that will allow relative motion between the two after a shear pin is broken by a flywheel housing torque of 3600 in-lb.

In order to reduce flywheel windage, the housing is evacuated during operation. A single system provides lubrication and vacuum, with a single Gerotor pump driven by a small 70 watt 12 vdc motor. Carbon face seals are used on the input and output shafts, while all other required seals are static.

The sizing of the flywheel bearings was based partly on a consideration of the gyroscopic torque reactions. It was assumed that normal angular rotation of the flywheel package (i.e., of the vehicle) would be 0.2 rad./sec. or less, with occasional rates to 0.5 rad./sec. The corresponding gyroscopic torques would be 563 and 1407 ft-lb respectively. The bearing sizes were chosen so as to have a minimum expected fatigue life of 4,000 hours based on all expected loads.

It is interesting to note that with the Pinto tread of approximately 54 inches and the above expected car motions, weight transfer from left to right wheels (or vice versa) caused by gyroscopic reactions would seldom exceed 63 lb., but occasionally could reach a level of about 150 lb. The car motions caused by gyroscopic torque reactions therefore appear to be significant for this flywheel vehicle, but not an overriding consideration.

At maximum flywheel design speed (10,000 rpm, giving 5,000 rpm at the input-output shaft), the total "windage" (no load losses) have been calculated to be 0.95 hp, including the electrical power required to run the lubrication-vacuum pump. The gear load losses are expected to be 2% of the transmitted horsepower.

4.0 CONTINUOUSLY-VARIABLE TRANSMISSION (CVT) DETAILS

4.1 Introduction

A continuously-variable transmission (CVT) is required to match the flywheel and vehicle speeds under all operating conditions. The CVT must have high average efficiency over a driving cycle if good fuel economy is to be obtained. During the preliminary design stages, it was not found possible to locate a commercially-available CVT suitable for the flywheel vehicle. It was determined, based on the time and monetary constraints of the program, that the best approach would be to design and construct a CVT at the University of Wisconsin, based on the power-split hydrostatic principle, using commercially-available hydrostatic components.

4.2 Design Specifications

The CVT has been designed to meet the following specifications:

Output torque capability	400 ft-lb
Ratio range	3.47
Output speed range	333-3,000 rpm
Corresponding input speed range	500-4,500 rpm
Control	torque control, based on position signals from accelerator & brake pedals

The efficiency characteristics of the CVT (more advantageously considered in terms of friction and other energy losses) were to be made as good as the time and money constraints of the program would allow, while meeting the above performance specifications with satisfactory reliability.

Fig. 4.1 Assembly drawing of the hydrostatic power-split continuously-variable transmission

4.3 Design Details

A detailed assembly drawing of the CVT is given by Fig. 4.1. Power comes into the unit (when the flywheel is driving the car, that is) at the left through the driveshaft universal joint. Most of the power is carried straight down the main shaft, but part is taken off through the chain drive at the left to drive the hydraulic pump. The stroke of the variable displacement pump is set by the Variable Pressure Control Valve to that value which will give the hydraulic pressure corresponding to the torque signal from the accelerator or brake pedal. The hydraulic pump and motor are connected by a pair of aluminum manifold blocks.

The two components of power (that transmitted through the main shaft, and that coming from the hydraulic motor via the chain drive at the right) are added in the internal spur gear differential. A cross-section view of this differential is given by Fig. 4.2. By carrying most of the power through the straight mechanical path, the average efficiency of the power-split hydrostatic CVT is greater than if a plain hydrostatic CVT were used.

The Sundstrand Series 20 hydrostatic pump and motor are used. The pump has a maximum displacement of $2.03 \text{ in}^3/\text{rev}$, and its stroke can be varied to provide displacements at any value between full positive and full negative. The motor has a fixed displacement of $2.03 \text{ in}^3/\text{rev}$. As mentioned earlier, the control is handled through a Sundstrand Variable Pressure Control Valve which bolts directly to the pump housing.

Although not shown on the assembly drawing (Fig. 4.1), the hydrostatic pump and motor require a reservoir, filter, charge pump, and associated tubing and hoses. The location of these items can be seen in Fig. 4.3. It may be necessary to add an oil cooler to the system, but this will be determined from monitoring hydraulic fluid temperature during all system tests.

HyVo chain drives are used for the hydraulic pump and motor. These have the advantages of very high efficiency, some tolerance to misalignment, and are convenient to use with our shaft center distances.

GEAR SPECIFICATIONS

Type : Involute Spur Gear , 20° Press. Angle

Pitch : 20 Diametral Pitch

Pitch Dia. : 5.40 in.

No. of Teeth : 108

Fig. 4.2 Cross-section of the internal spur gear differential of the continuously-variable transmission (CVT)

Fig. 4.3 The reservoir and charge pump for the continuously-variable transmission

Fig. 4.4 The internal spur gear differential sub-assembly for the CVT

Most of the CVT components have been built in the Mechanical Engineering machine shop at the University of Wisconsin, with a few items (sprockets and gears) subcontracted out.

Figures 4.4, 4.5, 4.6, 4.7, 4.8, and 4.9 are photographs of the various CVT components and subassemblies, while Fig. 2.9 shows the completely assembled CVT mounted in the Pinto.

Fig. 4.5 Bearing plates and universal joint yoke
for the CVT

Fig. 4.6 Morse Hy-Vo chain, sprockets, and chain covers for the CVT

Fig. 4.7 Checking the bearing alignment in the CVT case by use of a special dummy shaft

Fig. 4.8 Manifold blocks to connect the hydrostatic pump and motor

Fig. 4.9 Machining splines on the short shaft

5.0 ENGINE MODIFICATIONS

5.1 Introduction

The 4-cylinder 2.3 liter Pinto engine is used in the FEMP. The basic mechanical components have been left stock, but significant modifications have been made to the fuel and ignition systems. A Bosch "L-Jetronic" fuel injection system has been installed with a specially constructed intake manifold, and an adjustable EGR (exhaust gas recirculation) control valve. The ignition system has been modified to give a different spark advance curve. The engine modifications were all performed at Ford Motor Company by their personnel specifically for this program. Figure 5.1 shows the appearance of the modified engine.

5.2 Fuel Injection System

The L-Jetronic system is a Bosch-Ford developmental fuel injection system. In addition to the basic system, a special air-fuel (A/F) ratio adjustment box (Fig. 5.2) has been installed. The L-Jetronic fuel injection system is a feedback sensed system with an exhaust λ (LAMBDA) sensor. The λ sensor is not installed in the fuel injection system at the present time. A dummy electronic load is substituted. The adjustment box allows quick adjustments to the A/F ratio without major modifications. Further, the A/F ratio change is consistent throughout the engine operating range because of the feedback system. Besides the A/F ratio adjustment system, there has been installed a fuel cutoff system which can shut off the fuel flow at the injectors. This is necessary for the type of engine operation used in the FEMP. It is anticipated from initial tests at Ford Motor Company that this fuel cutoff system will eliminate emission problems with the start-stop operation of this engine. No major problems with the "on-off" method of operation are anticipated, but this will be confirmed by experimental testing.

5.3 Exhaust Gas Recirculation

Exhaust gas can be returned from the exhaust

Fig. 5.1 Front view of the modified engine, showing exhaust gas recirculation (EGR) system (tube and valve in center, just in front of air intake ducting)

Fig. 5.2 The special Bosch air-fuel ratio adjustment box, located in the driver compartment

manifold to the intake manifold through a specially constructed system. The amount of exhaust gas recirculation (EGR) is controlled by a "butterfly" valve mounted in the return tube (Fig. 5.1). The valve opening is controlled by setting its angular position and locking it in place. Since the engine in the FEMP is to be run only under wide-open throttle conditions, this system provides adequate control. EGR flow rate is proportional to engine power and therefore a constant percentage of exhaust gas is maintained for a given setting. The system is dependent on exhaust back pressure and above-the-throttle-valve air pressure.

5.4 Ignition Timing

Only simple modifications are made to the spark timing of this engine. Basically the system operates without vacuum advance, incorporating only centrifugal or speed sensitive advance. Advance characteristics are changed by (1) different sets of springs and (2) different idle or initial settings.

5.5 Exhaust System

The exhaust system has been set up initially with no catalytic reactor (removing the one that came stock on the Pinto). Because of the flywheel and CVT installations, it has been necessary to reroute the total exhaust system. It can be best described as very ordinary, corresponding to any stock exhaust system (without converter) for this class of vehicle. Exhaust system back pressure is the most important variable.

The vehicle testing program will allow us to determine whether or not a catalytic reactor is required for satisfactory vehicle emission performance.

6.0 SYSTEM AND COMPONENT TESTS

6.1 Introduction

The primary reason for constructing the Pinto FEMP vehicle was to obtain first hand experimental data that will allow the critical evaluation of the flywheel concept. It is therefore very important to run a wide range of accurate tests to determine its performance over different types of driving cycles and with various system adjustments and modifications. In addition to tests on the total vehicle, it is just as important to run comprehensive tests on the major system components to determine insofar as possible the reasons for the overall system performance.

Up to this time, a number of tests have been run on individual components, but only limited testing, mostly subjective, has been accomplished with the total vehicle. The testing program will be continued and expanded during the coming year.

6.2 Tests of Total Vehicle

To date, the testing of the total vehicle has consisted of (1) driving in parking lots and roads adjacent to the University of Wisconsin Engineering campus and Ford Motor Company grounds, and (2) a series of runs made in August, 1976 on an EPA type chassis dynamometer at the Ford Motor Company in Dearborn, Michigan. The chassis dynamometer tests were extremely useful for determining whether or not the car could be made to follow the EPA cycle by a professional driver, whether or not the FEMP system was rugged enough for the cycle, and how the actual engine on-off schedule compared with the theoretical schedule. Unfortunately, it was not possible to obtain valid fuel consumption and emissions numbers for the cycle because of a malfunction of the fuel injection system which caused the air/fuel ratio to be very low (about 10:1). A tight schedule and other factors made it impossible to repair the injection system in time to obtain a valid run.

Based on the general driving and the chassis dynamometer tests, a number of conclusions can be drawn. First of all, the general driveability of the car is very good, especially when one takes into account the control functions performed by the driver that would be automatically controlled in a production vehicle.

The torque control system operates smoothly and no tendency toward any unstable oscillations has been observed. It is felt to be completely satisfactory. Professional drivers at the Ford Motor Company were able to follow the EPA-CVS cycle with no great difficulty.

The regenerative braking has been found to be effective, smooth and readily implemented. There is the potential problem in the research vehicle of not shifting down into the required lower gears quickly enough, and thereby losing the regeneration capability. This consideration would not be present, however, in a production vehicle in which transmission functions were handled automatically.

The FEMP system has adequate ruggedness for any reasonable type of driving cycle. The EPA cycle itself provides quite a rugged workout for a car. In addition to running a number of these cycles, there were instances on the dynamometer when very high torque was applied. This would occur when the driver had to "catch up", and also when a bad shift was made or the clutch let out too fast. The single failure that has occurred in the FEMP system took place with faulty clutch operation, and consisted of all the lining of the standard shift clutch being torn loose from the disk. With the extremely high torque capability of the flywheel system, it may be a good thing for the clutch to act as a "fuse" to prevent more costly and time-consuming failures in other components.

The mechanics of the on-off engine operation have been found satisfactory, except for some problems with the initial start-up that occur with the current configuration. For the initial starting, the starter motor spins up the flywheel very satisfactorily to about 900 rpm within about 45 seconds. When the engine is clutched in its speed is therefore about 450 rpm. An engine speed of 450 rpm has been found to be somewhat low with a heavy inertia

load such as the flywheel, especially when the engine is cold. The initial start technique currently used is to engage the clutch at 450 rpm, but then immediately disengage it so that the engine can be warmed up with no load. Once the engine is reasonably warm (a minute or so), it is carefully clutched to the flywheel with some slippage allowed to insure that it continues to fire smoothly, until it reaches about 800 rpm. At that speed the engine will run smoothly at wide-open throttle under the full inertia load of the flywheel. The starting difficulties could be corrected by causing the starter motor to spin the flywheel up to a higher speed, about 1600 rpm. This has not yet been done, however, because of the mechanical complexity involved in implementation. The present starting procedure should have virtually no effect on the fuel economy and emissions data generated by the research vehicle.

Once the initial start-up has been accomplished, the on-off engine operation appears to be completely satisfactory except for noise considerations. The clutch engagement is smooth with minimal operator skill, and coordination of the fuel switch and clutch operation is no problem. The clutch disengagement and fuel shut-off is likewise easy to implement. A second person in the passenger's seat is normally used for the engine start and stop operations, as it has been found that the remaining tasks tend to require the full-time attention of the driver. Again, these considerations would not be present in a production-type system with automatic controls.

The shifting of gears, and the corresponding clutch action can be handled satisfactorily by the driver with a minimum amount of practice. It does take some time, however, to become accustomed to the idea of the frequent gear shifts, and to learn to pay close attention to the gear shift meter rather than to follow one's instincts. Probably the most critical part of the gear shifting procedure is the clutch engagement after the gear change is made. The clutch must be smoothly engaged, allowing a period of slip of about 1/2 second; rather than using an abrupt engagement. The reason for this is that the CVT has no torque reference while the clutch is disengaged, so that the CVT must adjust its ratio to correspond to

the driver's torque signal (and the new gear ratio) during the time of clutch slippage. It takes on the order of 1/2 second for the pump swashplate to move from one extreme position to the other. The clutch engagement must occur over about the same amount of time in order to insure that the ratio will have time to adjust itself, otherwise there is a strong possibility of a high positive or negative (depending on chance alone) torque at the driving wheels. Actually, the effect is about the same as that occurring when the clutch of a conventional standard shift car is "popped", and the amount of skill involved in avoiding it is about the same. This aspect of driver skill would not be required, of course, in a vehicle having the shifting handled automatically.

The emissions aspects of the on-off method of engine operation have not yet been adequately determined. Preliminary engine tests (see Section 6.3 of this report) have indicated, however, that the emissions characteristics should be satisfactory.

The general performance of the CVT appears good although the efficiency is not as high as desired. The CVT noise is quite reasonable, at least for a research vehicle. Additional research and development work would be in order, however, to make the sound level of this type of CVT satisfactory for a production vehicle. With the limited range and type of driving that has been done to date, it is not possible to say whether or not a heat exchanger is required for the hydraulic fluid in order to handle any foreseeable type of driving situation. Oil temperature of a five gallon reservoir reached a comfortable 130-140°F on the EPA dynamometer after two hours of testing. This indicates losses are about as predicted.

No serious problems with the operation of the flywheel package have been uncovered, except for its part in the initial start-up operation. The noise of the spiral bevel gear pair is quite high under load, but simple gear noise abatement techniques should greatly reduce this aspect. The vacuum system might be improved to increase the vacuum beyond the currently observed value of about 21" hg. This would reduce the flywheel windage, but the windage in its current condition lies well within our design specification.

Even though valid fuel consumption figures have not yet been obtained, it was found that the number of charge cycles over the EPA-CVS cycle was essentially the same as predicted by the latest computer simulations. Based on this, the car in its current state but with correct fuel injection characteristics should achieve about 28 mpg. Component refinements and modifications over the coming year should improve this figure. The main component to be modified is the engine clutch. This clutch loses approximately 2-1/2 hp at 4500 rpm. A reduction in loss of this one item can greatly improve the fuel economy. If the clutch loss can be reduced by a factor of 10 as we feel it can, our originally predicted mileage should be achievable.

The reason for this high clutch loss is apparently due to the clutch plate spinning at high speed relative to the pressure plate and engine flywheel. To reduce the loss it is necessary to simply "open" the clutch further and to prevent the clutch plate from touching either pressure plate or engine flywheel. This redesign is underway under the next year's effort.

6.3 Engine Tests

A limited amount of testing of the modified Pinto engine has been performed to date. These tests were all done at Ford Motor Company on an EPA type chassis dynamometer when the modified engine was still in an otherwise stock car. In order to simulate as nearly as possible the full-throttle operation while bringing the flywheel up to speed, the dynamometer tests consisted of accelerating the Pinto from 20 to 50 mph in second gear at wide-open throttle with the dynamometer inertia set at 5500 lb. and the road load factor set at 34 hp for 50 mph. The times for this acceleration were on the order of 30 seconds, about the same amount of time required for the actual flywheel recharging. The engine speed over the 20-50 mph range (in second gear) went from 1700 to 4300 rpm., again about the same as would occur in a typical flywheel recharging.

The chassis dynamometer was instrumented to provide us with data on the instantaneous concen-

trations of CO, CO₂, HC, NO_x and O₂ in the exhaust, as well as engine speed and manifold vacuum, all recorded on strip charts as functions of time. Runs were made with variations in spark advance, air/fuel ratio, and EGR ratio, with an attempt to cover those conditions which would give the best possible combination of BSFC and emissions flow rates. To evaluate the various engine calibrations, we have calculated as accurately as possible for each test run the horsepower-seconds generated by the engine, the amount of fuel required to do this, and the total mass of each of the 3 pollutants. These numbers will allow us to find the approximate set of engine calibration factors to give the best fuel economy over the EPA-CVS cycle while just meeting the emissions standards. The final engine calibration will be determined using a trial and error approach by running a number of EPA-CVS tests with small variations of the calibration factors, with the engine data already available serving as a guide for the changes. The results of the engine calibration tests on the chassis dynamometer are presented in Table 6-1. A BSFC of about 0.50 lb/hp-hr appears feasible while meeting current emissions standards.

6.4 Hydrostatic Pump and Motor Tests

A fairly extensive test program on the hydrostatic pump and motor has been conducted at the University of Wisconsin [8]. The two units have been coupled to a pair of electric dynamometers capable of absorbing (or generating) a steady 40 hp. Higher power values are available for short periods of time by accelerating the large dynamometer rotors. The dynamometer testing has been valuable not only for obtaining power loss data over the full range of operation expected in the vehicle, but also for studying the performance of the Variable Pressure Control Valve, the adequacy of the electrically-driven charge pump system, and other characteristics of the total hydraulic system. The hydraulic test set-up is shown in Figs. 6.1, 6.2, and 6.3.

During the course of the testing it was found that the energy losses incurred under conditions of small swashplate angle (i.e., low pump displacement) were much greater than what we had assumed earlier

Table 6-1

Engine Calibration Studies, based on 2nd gear wide-open throttle accelerations from 20 to 50 mph on an EPA certification chassis dynamometer set at 5500 lb. inertia weight and 34 hp at 50 mph.

Test No.	Nominal A/F Mixture	EGR Valve Position	Secondary Air Injection	Spark Timing, Deg. BTDC	20-50 mph Time, Sec.	hp-sec developed in run	Total fuel consumed in run, g	Total NO _x , g	Total CO, g	Total HC, g	Ave. BSFC, lb/bhp-hr
A 1	-5%	0	No	+1	17	840	43.6	2.25	7.57	0.571	.45
A 2	-10%	0	No	+1	19	858	44.2	2.77	2.82	0.493	.45
A 3	-20%	0	No	+1	24	901	57.0	3.16	1.09	0.289	.55
A 4	+5%	0	No	+1	18	847	47.1	2.30	20.02	0.210	.49
A 5	+5%	10	No	+1	18	850	47.6	0.768	19.89	0.683	.49
A 6	-5%	10	No	+1	20	865	49.9	1.61	8.97	0.677	.51
A 7	-20%	10	No	+1	31	956	72.0	1.81	0.914	0.484	.66
A 8	-20%	20	No	+1	57	1173	119.0	0.991	1.70	0.590	.89
A 9	-5%	20	No	+1	31	956	74.8	0.944	17.40	0.952	.69
A 10	+5%	20	No	+1	26	920	69.5	0.528	30.81	0.988	.66
A 11	+5%	20	Yes (w/DV) *	+1	28	934	74.2	0.751	23.02	0.779	.70
A 12	+5%	20	Yes	+1	27	927	68.0	0.618	12.36	0.621	.64
A 13	-5%	20	Yes	+1	44	1065	113.1	1.35	7.85	0.811	.93
A 14	-5%	0	Yes	+1	20	868	50.1	2.72	5.12	0.373	.51
A 15	+5%	0	Yes	+1	18	851	44.5	1.42	9.52	0.294	.46
A 16	-20%	0	Yes	+1	28	933	66.5	3.47	0.831	0.395	.62

* with dump valve operating. For succeeding runs, the dump valve was removed.

Table 6-1 (continued)

Test No.	Nominal A/F Mixture	EGR Valve Position	Secondary Air Injection	Spark Timing, Deg. BTDC	20-50 mph Time, Sec.	hp-sec developed in run	Total fuel consumed in run, g	Total NO _x , g	Total CO, g	Total HC, g	Ave. BSFC, lb/bhp-hr
B 1	-5%	10	Yes	+1	26	920	64.8	5.07	3.95	0.473	.62
B 2	+5%	10	Yes	+1	23	894	59.4	4.35	9.41	0.354	.58
B 3	+5%	10	Yes	+1	22	883	55.4	4.13	8.55	0.394	.55
B 4	-5%	10	Yes	+1	24	900	57.6	4.61	3.59	0.430	.56
B 5	-5%	10	Yes	+1	22	880	58.5	3.47	15.34	0.420	.58
B 6	+5%	10	Yes	+1	23	892	69.0	2.33	22.45	0.200	.68
B 7	-20%	10	Yes	+1	22	879	53.4	3.98	10.00	0.373	.53
B 8	-20%	10	Yes	+1	22	883	54.5	4.08	9.88	0.394	.54
B 9	-10%	10	Yes	+1	27	924	62.1	1.58	2.03	0.439	.59
B 10	-20%	10	Yes	+1	110	1608	275.6	17.28	3.26	3.219	1.50
B 11	-20%	10	Yes	+10	28	933	59.0	2.16	0.83	0.805	.55
B 12	-10%	10	Yes	+10	22	883	48.9	2.81	1.32	0.680	.49
B 13	-5%	10	Yes	+10	18	850	41.8	2.01	4.83	0.410	.43
B 14	+5%	10	Yes	+10	18	850	44.8	1.25	11.54	0.420	.46
B 15	+5%	20	Yes	+10	22	883	54.3	0.94	16.39	0.489	.54
B 16	-5%	20	Yes	+10	23	892	53.6	1.41	7.56	0.499	.53
B 17	-10%	20	Yes	+10	26	916	57.2	1.56	3.11	0.649	.55
B 18	-20%	20	Yes	+10	50	1114	100.7	1.93	1.48	1.383	.79
B 19	+10%	20	Yes	+10	23	887	57.6	0.72	18.99	0.525	.57
B 20	+10%	10	Yes	+10	17	842	42.5	0.79	12.92	0.360	.44
B 21	+10%	0	Yes	+10	15	826	38.5	1.04	11.72	0.334	.41
B 22	+20%	20	Yes	+10	22	883	62.5	0.35	34.09	0.680	.62
B 23	+20%	20	Yes	-4	48	1098	119.3	0.26	21.01	0.989	.95
B 24	+20%	10	Yes	-4	31	966	81.8	0.43	16.30	0.365	.74
B 25	+5%	10	Yes	-4	31	957	74.5	0.95	8.35	0.219	.68
B 26	-5%	10	Yes	-4	32	966	77.0	1.41	8.14	0.590	.70
B 27	-10%	10	Yes	-4	38	1011	89.7	1.80	7.87	0.346	.78
B 28	-10%	0	Yes	-4	23	892	53.8	2.15	4.48	0.162	.53
B 29	-5%	0	Yes	-4	22	883	52.7	1.58	5.60	0.167	.52
B 30	+5%	0	Yes	-4	20	867	47.1	0.80	3.58	0.087	.48
B 31	+10%	0	Yes	-4	20	867	50.0	0.59	6.27	0.108	.51

Fig. 6.1 Dynamometer testing of the hydrostatic transmission (Sundstrand Series 20 pump and motor)

Fig. 6.2 The Sundstrand Series 20 variable displacement pump under dynamometer test, with the Variable Pressure Control Valve mounted

Fig. 6.3 The Sundstrand Series 20 fixed displacement motor under dynamometer test

on the basis of data extrapolation. Since efficiency under such conditions is of little interest to most users, such data have not been readily available. Based on this change, and other modifications of performance data based on our test results, the projected EPA-CVS mileage would change from 38 mpg to about 34 mpg (based on changes in the hydrostatic units only).

The results of our dynamometer tests on the hydrostatic transmission (pump and motor, coupled) are given by Figs. 6.4 through 6.9. These curves show torque loss (referenced to the input shaft of the pump) as a function of hydraulic motor output torque, speed ratio between the motor and pump, and pump rotational speed. The curves do not include the charge pump losses, as they are handled separately. The method of presenting the data was chosen to correspond to the way the computer simulation program was written: energy losses are calculated from the effective torque loss at the CVT input shaft.

6.5 Coast-Down Tests

One of the most significant sources of power losses that limit the fuel economy of a FEMP vehicle is the combined "spin losses" of the various components that are continuously rotating at a relatively high speed whenever the vehicle is being operated. These losses include such things as ball bearing friction, seal friction, wind resistance of the flywheel, clutches, gears, etc., and churning losses caused by gears running in an oil bath. Such losses are functions of speed alone (noting that additional losses are incurred when power is transmitted), and therefore it is possible to get accurate values of spin losses by "coast-down" test procedures.

A coast-down test consists of driving the device under study (e.g., the flywheel) up to a high speed, preferably the maximum design value, disconnecting the power, and then recording the speed as a function of time as the device slows down. By determining the deceleration rate at the various speeds, and knowing the effective polar moment of inertia, it is possible to determine the sum of the spin losses

Fig. 6.4 Hydrostatic transmission torque losses measured on dynamometer, for pump speed of 250 RPM

Fig. 6.5 Hydrostatic transmission torque losses measured on dynamometer, for pump speed of 500 RPM

Fig. 6.6 Hydrostatic transmission torque losses measured on dynamometer, for pump speed of 1,000 RPM

Fig. 6.7 Hydrostatic transmission torque losses measured on dynamometer, for pump speed of 2,000 RPM

Fig. 6.8 Hydrostatic transmission torque losses measured on dynamometer, for pump speed of 2,800 RPM

Fig. 6.9 Hydrostatic transmission torque losses measured on dynamometer, for pump speed of 3,500 RPM

acting on the device. By running a series of coast-down tests, with different combinations of components attached together, it is in many cases possible to separate out the spin losses of the various components.

With the exception of the one run at AiResearch, the coast-down tests were all based on spinning up the flywheel package with the Pinto engine to 4500 rpm, then declutching it and monitoring flywheel speed with time. Tests have been made with the following combinations of system components:

- (1) the flywheel package alone
- (2) the flywheel package and engine clutch (disengaged)
- (3) the flywheel package, engine clutch (disengaged), and standard shift clutch (engaged)
- (4) the flywheel package, engine clutch (disengaged), standard shift clutch (engaged), and four-speed gearbox (in each of the four gears and neutral)
- (5) the flywheel package, engine clutch (disengaged), standard shift clutch (engaged), four-speed gearbox (fourth gear), driveshaft, CVT, and rear axle assembly.

By taking the power losses of each run (at the various speeds) and subtracting the corresponding losses of the previous run, the losses of the item(s) added are obtained. With this approach losses as functions of speed have been determined for the following:

- (1) the flywheel package
- (2) the engine clutch (disengaged)
- (3) the standard shift clutch (engaged)
- (4) the four speed gearbox (in all four gears and neutral)
- (5) the combination of CVT, driveshaft, and Corvair rear axle assembly (including wheel bearings, seals, but no brake drag). This test was able to be run only with the hydrostatic pump at its full positive and full negative strokes.

The results are presented by Figs. 6.10 through 6.12. Since the runs were all made with the vehicle components in their original configuration, some of the losses may be lowered by subsequent modifications. In fact, the coast-down results will prove useful for indicating which components might benefit most from changes. It was found that the spin loss in the four-speed gearbox is virtually independent of what gear is engaged.

It is expected that the results of the coast-down tests will be extremely valuable in helping us to explain the reasons for the results obtained in the test program which is planned for the total vehicle.

Fig. 6.10 Spin loss characteristics as measured by coast-down tests with various combinations of FEMP components

Fig. 6.11 Spin loss characteristics of individual FEMP components as determined from coast-down tests

Fig. 6.12 Spin loss characteristics of the CVT as determined from coast-down tests

7.0 FUTURE WORK

7.1 Introduction

The three-year research program entitled "Increased Fuel Economy in Transportation Systems by Use of Energy Management" was completed in the summer of 1976, with this report (and the two previous final reports) covering the results. Research in this general area is being continued at the University of Wisconsin, however, through two new research contracts:

(1) Contract No. DOT-OS-60177, "Flywheel Energy Management Systems for Improving the Fuel Economy of Motor Vehicles", with the Office of University Research, U.S. Department of Transportation. Work under this contract will include some experimental testing of the FEMP research vehicle, but the main emphasis will be placed on the study of ways to improve the efficiency of the FEMP drivetrain system, in particular, the CVT.

(2) Contract No. DOT-UT-70037, "Flywheel Energy Management Powerplant System Evaluation", with the Urban Mass Transit Administration, U.S. Department of Transportation. The emphasis of this research work will be on experimental testing of the FEMP vehicle to determine its fuel economy and other performance characteristics, and to extend the data to urban mass transit vehicles.

7.2 Research Study of CVT's for Flywheel Vehicles, and Integration of all FEMP Components

A major phase of the coming year's work involves investigation of the mechanical details of the hardware components of the FEMP which are critical in determining its practicality as a true fuel-saving concept. Previous work has shown the CVT to be the most critical element of the system, and a comprehensive study of alternative CVT principles will be carried out. It is planned to consider in de-

tail four basic CVT concepts: (1) traction drive, (2) hydrostatic transmission, both the straight and power-split, (3) the electric power-split transmission, and (4) an improved multi-gear automatic transmission with two-way torque converter or slipping clutch. Most of this phase of the work will consist of analytical studies based on experimental data obtained from previous testing and from component manufacturers. A small amount of component testing may be done at the University of Wisconsin, however, to obtain important performance data that may be available from no other source.

Combined with the study of the various CVT concepts will be the consideration of the total FEMP. Designs in which all system components are integrated into a single package would greatly reduce the size and weight of the system, and furthermore could reduce friction losses by the elimination of certain gears, bearings, and other mechanical components. The possibility of front wheel drive (which offers improved regenerative braking) will be studied in this phase. Included in the design studies will be methods for automatic control of all system functions, and a consideration of the cost aspects of the system and its suitability for mass-production.

7.3 Test Program for the FEMP Research Vehicle

7.3.1 Objectives

The basic objective the the test program is to determine the performance characteristics of the FEMP vehicle. The two most important aspects are, of course, fuel consumption and emissions characteristics. In addition, other aspects of the flywheel concept are to be determined, such as the significance of gyroscopic reactions, practical aspects of regenerative braking, noise of the FEMP components, and general drivability.

In addition to determining the performance characteristics of the specific research vehicle that has been built, test data will be obtained that will allow an accurate prediction of what effect specific powerplant (engine-transmission)

changes would have on fuel consumption and emissions values.

The results of this evaluation program will allow the determination of the performance of similar vehicular systems with comparable components, that is, variations in the flywheel-drive train concepts, variations in vehicle types and sizes, and different vehicle applications.

Finally this program will allow the experimental verification of computer modelling and prediction techniques currently used.

7.3.2 Summary of Test Program

The early testing will be done at the University of Wisconsin. We anticipate that a certain period of time will be required to become accustomed to the characteristics of the FEMP vehicle, to work out minor "bugs" that will become apparent during this phase, and to develop and set up the equipment required to obtain actual performance data. An EPA type chassis dynamometer is to be installed at the University of Wisconsin late in 1976. In addition, an accurate fuel flow measuring system will be designed and constructed that is compatible with the unusual fuel system required for the Bosch L-Jetronic fuel injection system. Although only limited emissions measuring equipment will be available at this dynamometer, we will be able to determine good approximate emissions values by using what is available and by referring to the results of the engine testing previously performed (see Section 6.3). These chassis dynamometer tests will provide fuel consumption figures over different driving cycles with system component characteristics and operating parameters set at a number of different values. During these tests, the control system characteristics will be closely monitored to see if the changes studied affect its stability.

The car will also be driven at and around the University of Wisconsin on public roads and in parking lots to determine system characteristics that might be masked during the chassis dynamometer tests. During this driving, such things as control system

stability, practical aspects of regenerative braking, and the significance of gyroscopic reactions will be monitored.

Once the testing at the University of Wisconsin has progressed to the stage where we feel we understand the vehicle and its characteristics, and know approximately how it should be adjusted and driven to obtain best mileage, a series of precise tests will be done at an industrial laboratory having an EPA dynamometer with full emissions instrumentation. This will very likely be at the Ford Motor Company, although it could be done at the EPA Laboratories in Ann Arbor, Michigan.

The overall test program as outlined above should not be assumed rigid. With a research program of this type, new information is constantly becoming available, and may be found to affect the sequence and timing of the various stages of the tentative program.

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