SAE The Engineering Resource For Advancing Mobility 400 COMMONWEALTH DRIVE WARRENDALE, PA 15096

SAE Technical Paper Series

820389

Retrofit Feedback Control of A/F Ratio and Ignition Timing for Fuel Economy

J. E. Morris, Hugh Anderson, and Roy Smith
Physics Dept.
Univ. of Wellington
(New Zealand)

Reprinted from P-104—
"Electronic Engine Management
and Driveline Controls"

**International Congress
& Exposition
Detroit, Michigan
February 22-26, 1982**

820389

Retrofit Feedback Control of A/F Ratio and Ignition Timing for Fuel Economy

J. E. Morris, Hugh Anderson, and Roy Smith
Physics Dept.
Univ. of Wellington
(New Zealand)

ABSTRACT

An electronic engine management system has been developed to control both ignition timing and air-fuel (A/F) ratio to maximize fuel economy. Both controls employ feedback techniques and are therefore intrinsically adaptable to a wide variety of models, as required for a universal retrofit market. The ignition control loop monitors the position of the combustion pressure peak while the mixture control loop senses the lean limit as defined by a roughness threshold. Test results demonstrate fuel economy and transient operation. A brief background to the New Zealand energy conservation program is in included as background to the system's specification.

THE DEVELOPMENT OF ELECTRONIC ENGINE MANAGEMENT in North America and Japan was driven initially by the need for tight emission controls. More recent demands for improvements in engine efficiency are not entirely compatible with the original objective and have led to increasingly complex control systems. At this stage Britain and Europe also appear to be headed along the same general track. These integrated systems comprise closed-loop feedback control of air-fuel mixture and open-loop scheduling of ignition timing.

The three-way catalyst necessary for the simultaneous oxidation of the HC and CO and the reduction of the NO_x components of the exhaust gases requires a stoichiometric fuel mixture. Rich and lean deviations from this condition are monitored as the absence or presence of O_2 in the exhaust gases. The detector acts as a simple switch and the mixture oscillates around stoichiometric. In principle, and in its elementary form, such a controller could be fitted to any vehicle since there is no vehicle-specific parameter involved.

By contrast, the determination of optimum ignition timing for a given combination of measured rpm and load is being achieved by look-up table techniques. The tabulated values stored in ROM, however, must first be established by exhaustive testing. These tables (or maps) vary dramatically from engine to engine and it would be impossible to expect satisfactory performance from an ignition control device developed for a different vehicle.

These solutions to the engine management problem were originally developed to meet the needs of North America and are also undoubtedly appropriate to countries with urban air pollution problems. Along with various other countries, however, New Zealand has no significant difficulty with air pollution and must consider its own course of development.

NEW ZEALAND'S REQUIREMENTS

Energy conservation in general and fuel economy in particular have assumed an increased importance in the world since the price escalations of the 1970's. The economic problems these have brought are particularly severe for countries like New Zealand who depend $100^o/o$ upon imported oil. Other international trading factors have contributed to a general deterioration of the balance of payments and a long-term policy of internal energy self-sufficiency. The first parts of the program, conversion of $10^o/o$ of the 1.5 million car fleet to CNG (compressed natural gas) and a similar switch of commercial vehicles to LPG (liquified petroleum gas), are well underway. Accelerated oil exploration programs are showing encouraging results and research activity into the use of both M15 and M85 (15°/o and 85°/o methanol:petrol mixtures) is well advanced. Methanol and derived synthetic petrol are to be produced in large scale plants currently under construction. Ethanol, producer gas and rape seed oil are being developed for farm use. The scale of this activity must be related to the resources of an agricultural producer of 3 million population to be appreciated.

The purpose of the thumbnail sketch of the country's diverse approaches to fuel conservation is to make the point that it is a prime economic objective. By contrast, no priority has been given to constraints on exhaust emissions. This is not because New Zealanders are any less environmentally aware than the rest of the world. Industrialization is relatively light, however, and traffic densities are similarly low with prevailing coastal winds clearing any potential problems. Only one city suffers occasional smog and its legislated emission limits are easily met by conventional vehicles.

The term "conventional vehicle" is used here to mean one with no form of emission control. While electronic ignition, breakerless ignition and early 1970's type emission controls are creeping in on some models, new cars even now are generally "conventional." In addition, the relatively large national fleet is characterized by high average age (9 years) and high average vehicle lifetime (23 years)(1)* - the result, no doubt, of new car prices typically 50°/o higher than in the U.K. The expected lifetime length of the existing fleet means that national fuel conservation efforts must also include the development of retrofit aids to fuel efficiency.(2) Higher fuel costs in proportion to take-home pay make the purchase of a sufficiently effective system much more attractive to both commercial operators and the general public than it would be in North America. But no significant engine modification is possible at the price which must be met.

The other element to be considered in setting the specification of a retrofit fuel economy system is the range of models to be covered. Over twenty-five basic passenger models are assembled locally with a similar number imported directly. To perform systematic individual tests on all these would be a daunting task and any retrofit system must adapt readily to all to be practicable. In particular, the conventional memory map approach to ignition control has been discarded on account of the time required for systematic testing.

It is clear from the above that the retrofit engine management system to be developed must control both ignition timing and fuel mixture by feedback systems. Furthermore, the parameter which is sensed in each case must not be a parameter which varies greatly from engine to engine. No expensive componentry can be contemplated; fuel injection cannot be substituted for carburetion, for example. It would also be highly desirable if the unit could be fitted and set up by the home-handyman without recourse to specialized skills or equipment. General targets were set at the outset; it was felt that lean-limit control would yield 10°/o economy with a further 5°/o gain from ignition control. Allowing 5°/o for the "tune-up" effect gained from continuous control, a net economy target of 20°/o sets a retail price target of $200 for an arbitrary two year payback period for the average private motorist. The system outlined below has been developed to meet these criteria. The targets above have not yet been achieved, but are not far off.

MIXTURE CONTROL

Experimentally, maximum fuel economy is determined to lie on the lean side of stoichiometric.(3,4) (Note that the New Zealand fleet still functions on the rich side of this point, with leaded fuel burned in relatively high compression engines.) The prime objective of maximum fuel economy before anything else therefore clearly dictates operation at some point in the lean-burn region.

As one moves away from the stoichiometric point, engine roughness develops(3,4) and can be used as a feedback test parameter to determine the mixture of maximum fuel economy. Although emission control is not a significant objective of the engine controller, the point of maximum fuel economy appears to coincide roughly with that of maximum HC and CO suppression with substantial reduction of NO_x. (5)

The trick, then, is how to measure roughness and quantify it for comparison with some empirical threshold. A variety of techniques have been, are being and will be investigated for this. The general system approach is that described by Leshner.(5) An air admittance valve is provided to bypass airflow around the carburetor directly into the inlet manifold. This valve is incrementally opened until a roughness figure greater than threshold is encountered. At this point the valve rapidly closes by some preset amount

---

*Numbers in parentheses designate references at end of paper.

before beginning once more to open incrementally. Mixture is therefore effectively leaned out by increasing the roughness threshold. As in most other similar systems described in the literature, Leshner et al sense flywheel acceleration to evaluate engine roughness. In the data presented below, roughness is determined by a 3-point smoothing algorithm and normalized nonlinearly to rpm. (The numbers quoted are on an arbitrary scale.)

A block diagram of both mixture and ignition control systems is provided in Fig. 1.

IGNITION CONTROL

There are two main approaches to feedback control of ignition timing described in the literature. Schweitzer and Collins(6) describe the dither technique whereby the effects of small changes in ignition timing on engine performance are measured to continuously evaluate the current ignition timing for engine efficiency. Such tests occupy time, and while this is unimportant for steady state performance, it constrains the system's transient response. For this reason mainly, the alternative approach of Powell and coworkers(7-10) was pursued from the outset.

The algorithm is based upon the empirical result that the crank angle at which the intra-cylinder combustion pressure reaches its peak value varies very little as the ignition timing is varied widely to maintain optimum fuel economy over the extremes of other engine variables.(11) One must therefore determine the position of the cylinder pressure peak and advance or retard ignition timing depending on whether the peak arrives early or late. Cylinder pressure may be monitored by a simple piezoelectric ring transducer fitted under the sparkplug as described by Kondo(12) and Powell.(7-10) As the combustion pressure develops, the compression on the ring, which is fitted under the sparkplug in lieu of the usual washer, is relieved and an inverted pressure signal derived.

The piezoelectric sensor has also been shown to act as an effective knock detector. Narrow-band filtering eliminates the pressure peak signal and mechanical noise at lower frequencies and electrical noise at higher prior to amplification of the signal at the characteristic knock frequency.

COMPLETE CONTROL SYSTEM

The engine controller is based on the Motorola MC6803 microcomputer chip which contains sufficient RAM for temporary storage and internal timing capability. The program occupies less than 1K of EPROM and an MC6801 can therefore replace the MC6803 in production quantities. At 3000 rpm the MPU is occupied for less than 10°/o of the time.

The air-bypass valve is a simple gas-cock driven by a fast 90° high-torque pulse-controlled servo from a model airplane. Two crank position markers 180° apart are employed for a 4 cylinder engine and may be detected by any of the conventional techniques. The single piezoelectric washer pressure sensor may be fitted to any cylinder. Electronic ignition is included within the electronics package which is normally positioned in the engine compartment.

SYSTEM TESTING

Four distinct testing procedures have been set up. For the moment these all run on a 1976 1.3 litre British Leyland Marina van which has been fitted out for the purpose with an extended electronics package in the passenger compartment (Fig. 1). The control system may be quickly changed between four operational modes:

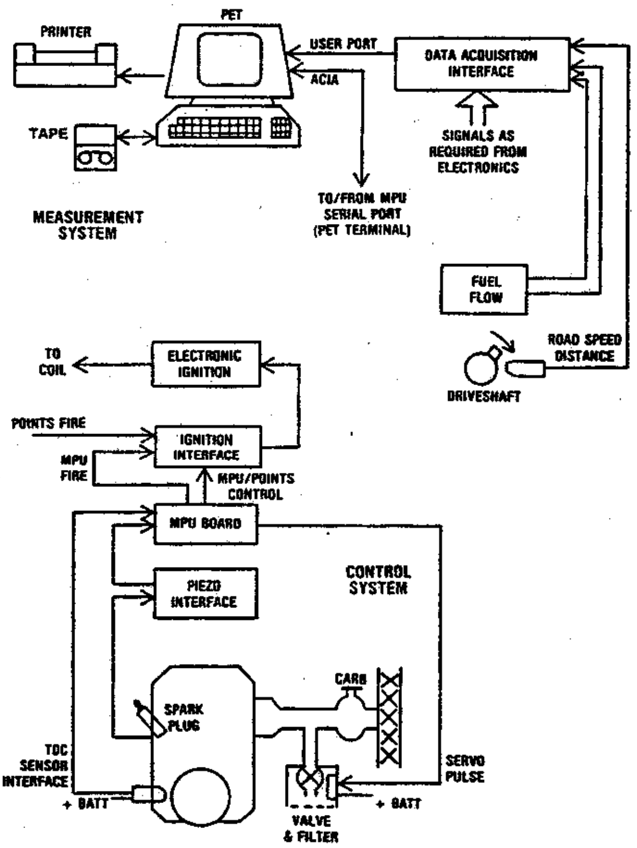


Fig. 1 - Block diagram of mixture and ignition control systems and of the monitor equipment in the van

(a) Full control as described; optimum pressure peak angle may be set within design range; roughness threshold, choice of smoothing algorithms and roughness sensing techniques are similarly switch-selectable.

(b) Air bypass is disabled by simply specifying a zero roughness threshold; the valve is then driven fully-closed.

(c) Ignition control is similarly switch-disabled; the non-standard electronic ignition remains as coil-driven, however, but is triggered by the vehicle points.

(d) Clearly, both controls may be disabled but note that the electronic ignition remains.

As a background task the 6803 uses its serial data port to transmit asynchronous status data from RAM (rpm, pressure peak position, roughness level, etc.) to a VDU terminal. This terminal function is actually provided by software control of a Commodore PET microcomputer installed in the van. An ACIA has been installed in the PET to supply serial communication. This setup is a useful diagnostic aid.

The van is equipped with an Ono Sokki FP214 fuel flow meter. An interface decodes the quadrature meter signals into forward and reverse flow pulses; these and other relevant pulse inputs (TDC, pressure peak(s), ignition fire, bypass valve servo pulses, distance traveled) are passed from the interface in standard format to the 6522 VIA (USER port) on the PET. These signals are interpreted by three distinct analysis programs.

The first of these is designed to build up a library of fuel consumption records over standard routes under normal road driving conditions. A speed profile for the drive is also recorded for comparison with other records over the same route.

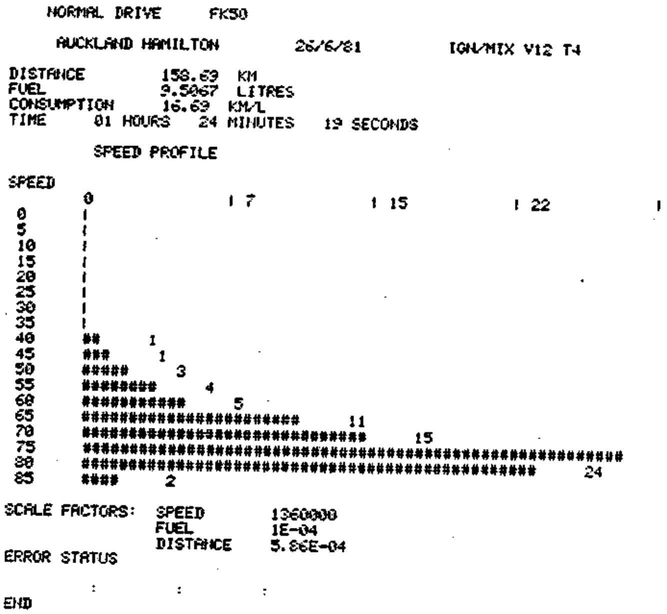
Eventually, fuel economy comparisons must be based on the appropriate standard drive cycle,(13) and another program is being written for this purpose. Most of the program is concerned with providing driver aid in the form of coded tones to facilitate driving to the standard. Deviations from the nominal curve and fuel consumption over each section will be recorded along with the main figure of total fuel use.

The fast data acquisition system was again developed as a diagnostic tool. Every engine and electronic system event of interest is detected and stored in PET RAM as an identification code with time of occurrence until available memory is full. In most cases this provides a continuous record of system operation over half a minute or so; this is more than adequate to analyze controller response to transients, for example. (Transient response has not yet been systematically studied, but no obvious problems have appeared.)

The data is then dumped onto cassette for later analysis in the laboratory by a second PET equipped with dual floppy-disc and Watanabe MIPLOT digital plotter.

TEST RESULTS

An example of the road-drive profile printout is presented in Fig. 2.



```
   NORMAL DRIVE     FK50

    AUCKLAND HAMILTON          26/6/81            IGN/MIX V12 T4

DISTANCE          158.69  KM
FUEL              9.5067  LITRES
CONSUMPTION       16.69  KM/L
TIME      01 HOURS   24 MINUTES   19 SECONDS

        SPEED PROFILE

SPEED
        0                ! 7              ! 15              ! 22              ! 30
 0      !
 5      !
 10     !
 15     !
 20     !
 25     !
 30     !
 35     !
 40     ##      1
 45     ###      1
 50     #####      3
 55     ########      4
 60     ###########      5
 65     ########################      11
 70     ###############################      15
 75     ############################################################      29
 80     ##################################################      24
 85     ####      2

SCALE FACTORS:   SPEED        1360000
                 FUEL         1E-04
                 DISTANCE     5.86E-04
ERROR STATUS

END
```

Fig. 2 - Example of road-drive printout

These records can hardly be classified as scientifically valid, but provide a useful continuing form of informal feedback to the development group. According to comparisons of these records, the controller achieves economies of around 12°/o on the highway. The system has yet to be optimised to the standard N.Z. drive cycle. Nevertheless, fuel economy being achieved over the standard is currently 5.8°/o with mixture control alone (Fig. 3).

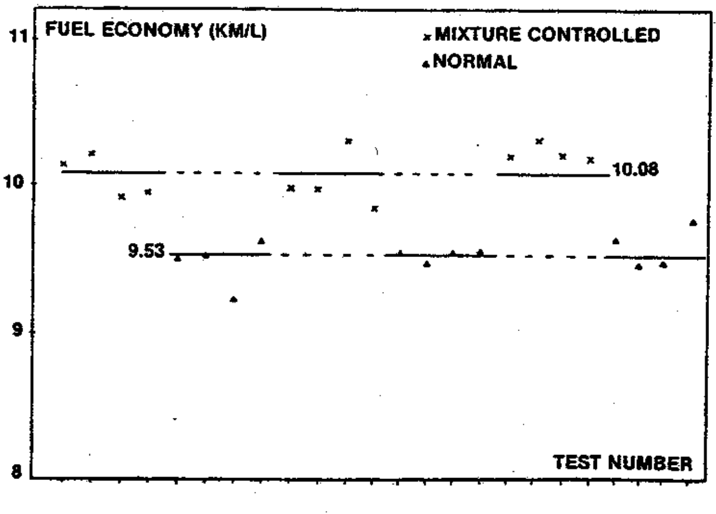


Fig. 3 - New Zealand drive cycle road tests

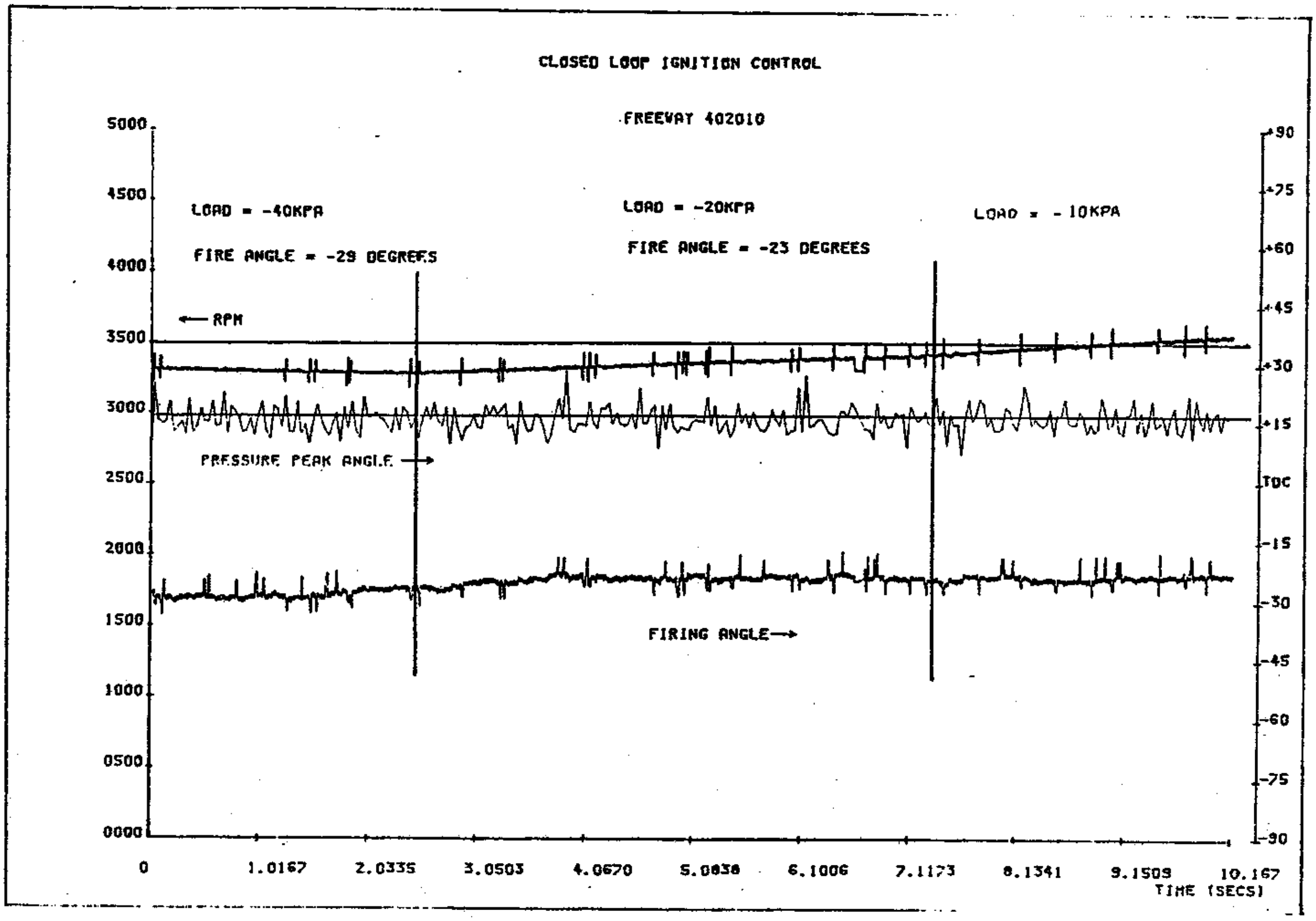


Fig. 4 - Variation of ignition timing to maintain peak position

Controller function is illustrated in Figs. 4 to 10 which have been obtained by the fast data system described above. Figure 4 shows the variation of firing angle to maintain constant pressure peak position under near steady state conditions of slow acceleration. Note that although the average peak position is well controlled, there is considerable random fluctuation from engine cycle to cycle. In Fig. 5, which illustrates the change in pressure peak position (combustion rate) with load, the decrease in peak position dispersion with increased load is also demonstrated.

Figure 6 also introduces the problem of using the pressure peak algorithm at idle or low load. The peak position trace in Fig. 6 bottoms out at TDC on overrun. This is because the combustion peak vanishes or is overshadowed by the compression peak which obviously reaches its maximum at TDC. To circumvent this problem, a minimum advance curve similar to the centrifugal one overrides the control algorithm; see Fig. 6 where the tendency to retard at overrun is held to 18^{0} BTDC. Figures 6 and 7 give some indication of transient response time of the ignition control system to changes.

All preceding figures were taken without functioning mixture control. In Fig. 8, the effect of the air bypass is shown, the valve being deliberately closed for about 5 seconds. With the valve open and a weakened fuel mixture, combustion time increases. To compensate, ignition timing must advance to hold pressure peak position constant. As the mixture leans out, the dispersion in peak position increases. The roughness figure which determines valve opening is also shown on the diagram.

The performance feature of interest, however, is fuel economy and the road-drive routine has been used to gather reasonably consistent data with the Marina van on a chassis dynamometer (rolling road). Each point on Figs. 9 and 10 represents consumption of about 0.5 litre of fuel; the dynamometer load setting was constant for Fig. 9 (150 mv), although uncalibrated,

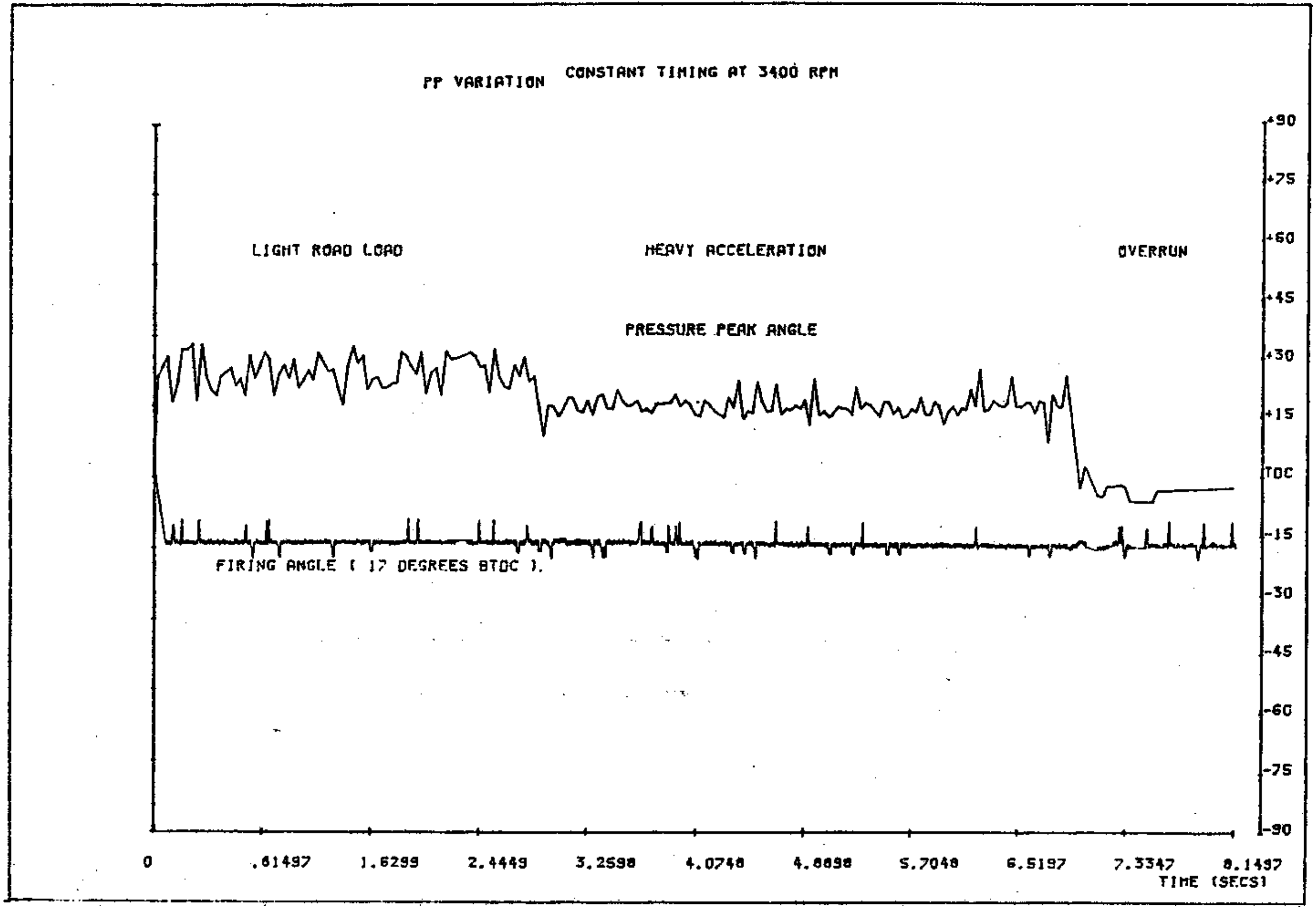


Fig. 5 - Variation of peak position with engine load for fixed timing

and roughly represents cruising conditions. Fuel consumption without mixture control (roughness threshold zero) and the optimum roughness threshold for each speed setting are shown in Fig. 11. Significant savings are clearly indicated. As load is increased (Fig. 12) the potential economy is reduced but the peak sharpens and moves to a higher roughness threshold. The variation of optimum threshold with rpm is easily handled by software, but compensation for the load effect would require additional hardware.

Figures 9 to 11 were established with standard ignition timing from the points. For Fig. 12 the optimum pressure peak angle was set to 18.5° ATDC. Fuel consumption variation with control angle is shown in Fig. 13, but the economy peak is neither as sharp nor as large as expected. There is evidence that peak position control broadens the mixture economy peak. Work is continuing on the ignition control system.

The other important feature of controller performance is driveability. Surging is definitely detectable at high roughness threshold settings, but the optimum fuel economy value generally corresponds to the point where this effect totally vanishes. Certainly, experienced drivers in the automotive business do not seem to be able to detect whether the controller is functioning or not at this setting.

CONCLUSION

This paper has briefly described the development and testing of a retrofit electronic ignition and mixture control system for the improvement of fuel economy. More detailed and specific information on system hardware and software, design alternatives, the test systems and development tools are available from the New Zealand Energy Research and Development Committee. (14,15) In addition, the data and analysis system is described in more detail elsewhere.(16)

The unit described here and tested to date is only a prototype. Development is continuing with transducers, electronics and software all under review and re-design. One area of importance not yet begun is the study of the emission characteristics of the

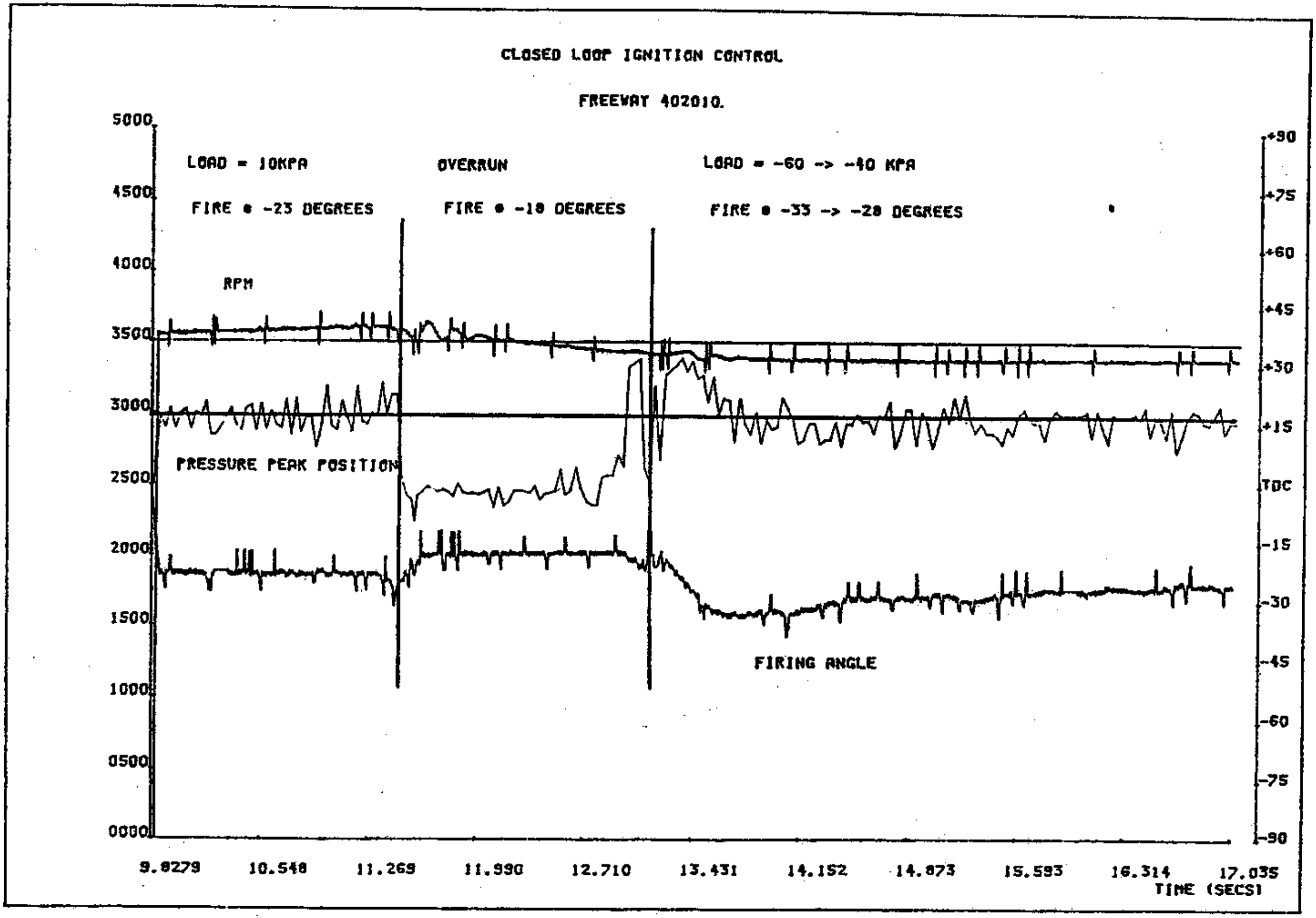


Fig. 6 - Demonstration of no-load peak behavior and timing retardation limit

system. There is no adequate equipment in New Zealand for this task.

The work reported here was carried out in the Physics Department, Victoria University of Wellington, New Zealand supported by New Zealand Energy Research and Development Committee Contract 3119. The active assistance of the Department of Mechanical Engineering, University of Auckland and of the New Zealand Motor Corporation who provided the test vehicle are gratefully acknowledged.

REFERENCES

1. T. A. Bone (Beca Carter Hollings and Ferner Ltd.) "Differential Supply and Pricing of Motor Vehicles," NZERDC Contract 3108, Interim Report, September, 1978.*

2. J. E. Morris, "Automotive Engine Management Systems," N.Z. Energy Research and Development Committee Report P19, August, 1979.*

3. J. F. Cassidy, "Emissions and Total Energy Consumption of a Multicylinder Piston Engine Running on Gasoline and a Hydrogen-Gasoline Mixture," NASA publication TN D-8487, 1977.

4. M. D. Leshner, C. A. Luengo and F. Calandra, "Brazilian Experience with Self-Adjusting Fuel System for Variable Alcohol-Gasoline Blends," SAE paper 800265.

5. M. D. Leshner, J. W. Stuart and E. Leshner, "Closed Loop Control for Adaptive Lean Limit Operation," SAE paper 780039.

6. P. H. Schweitzer and T. W. Collins, "Electronic Spark Timing Control for Motor Vehicles," SAE paper 780655.

7. M. Hubbard, P. D. Dobson and J. D. Powell, "Closed Loop Control of Spark Advance Using a Cylinder Pressure Sensor," ASME paper 75-WA/Aut.17.

8. R. J. Hosey and J. D. Powell, "Closed Loop, Knock Adaptive Spark Timing Control Based on Cylinder Pressure," ASME paper 78-WA/DSC-15.

9. K. W. Randall and J. D. Powell, Contract DOT-OS-3011 final report, May 1976, U.S. Department of

*NZERDC reports are available from the N.Z. Energy Research and Development Committee, University of Auckland, Private Bag, Auckland, New Zealand.

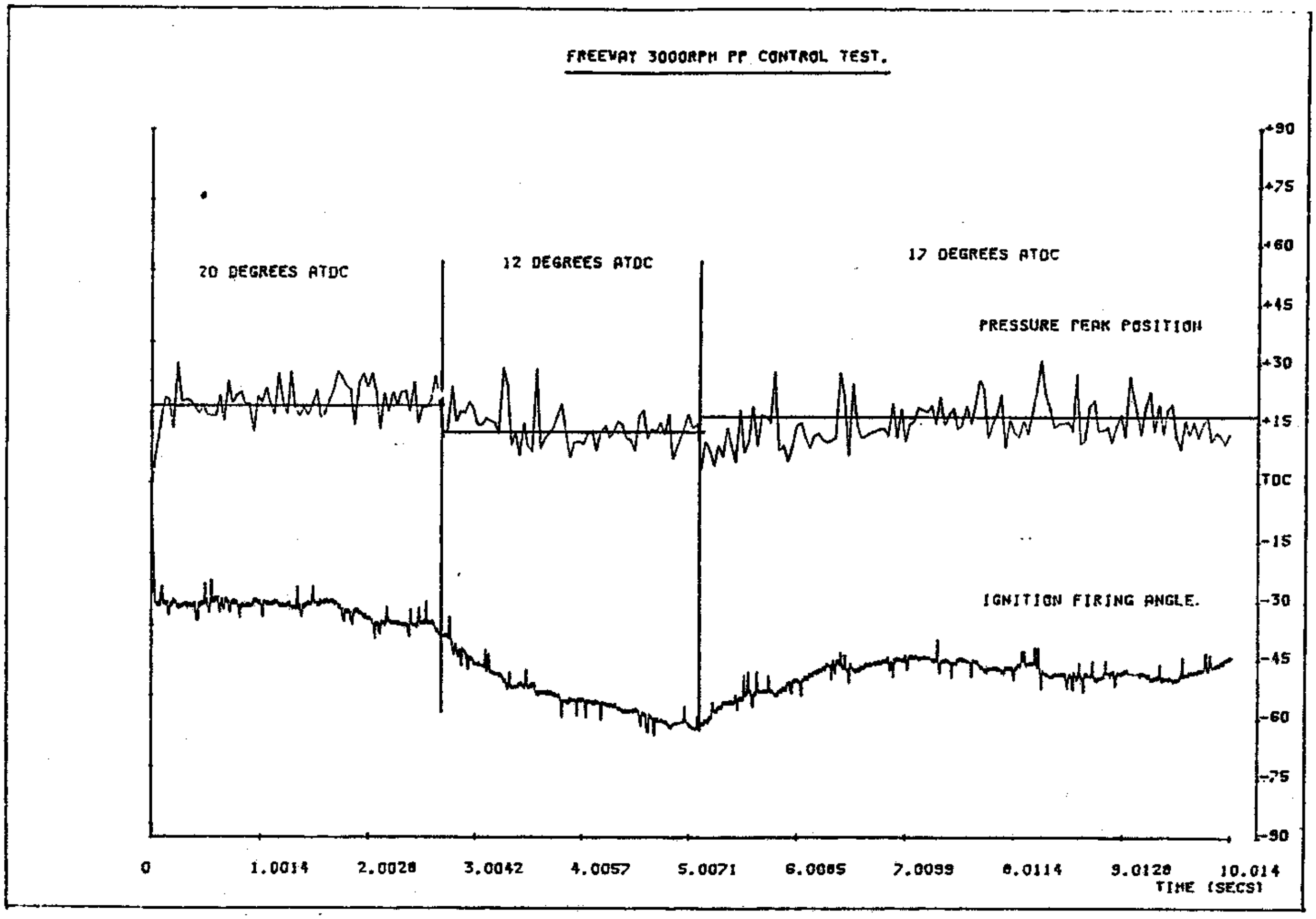


Fig. 7 - Ignition timing response to pressure peak control angle changes

Transportation publication DOT-TST-76-107.

10. K. W. Randall and J. D. Powell, "A Cylinder Pressure Sensor for Spark Advance Control and Knock Detection," SAE paper 790139.

11. J. B. Heywood, J. M. Higgins, P. A. Watts and R. J. Tabaczynski, SAE paper 790291.

12. M. Kondo, A. Niimi and T. Nakamnara, "Indiscope - A Non Combustion Pressure Indicator with Washer Transducers," SAE paper 750883.

13. Standards Association of New Zealand, N.Z. Standard NZS 5420:1980, "Methods of Test for Petrol Consumption of Passenger Cars."

14. J. E. Morris, "Instrumentation of Cars for Fuel Economy: NZERDC Contract 3119 Final Report," N.Z. Energy Research and Development Committee, Report 70, October 1981.*

15. J. E. Morris, "Instrumentation of Cars for Fuel Economy: Appendices to Report 70," N.Z. Energy Research and Development Committee Publication PSI, October 1981.*

16. J. E. Morris, Roy Smith and H. Anderson, "Data Acquisition and Analysis in a Vehicle with a Commodore PET," submitted to J. Phys. E.: Sci. Instrum.

---

*NZERDC reports are available from the N.Z. Energy Research and Development Committee, University of Auckland, Private Bag, Auckland, New Zealand.

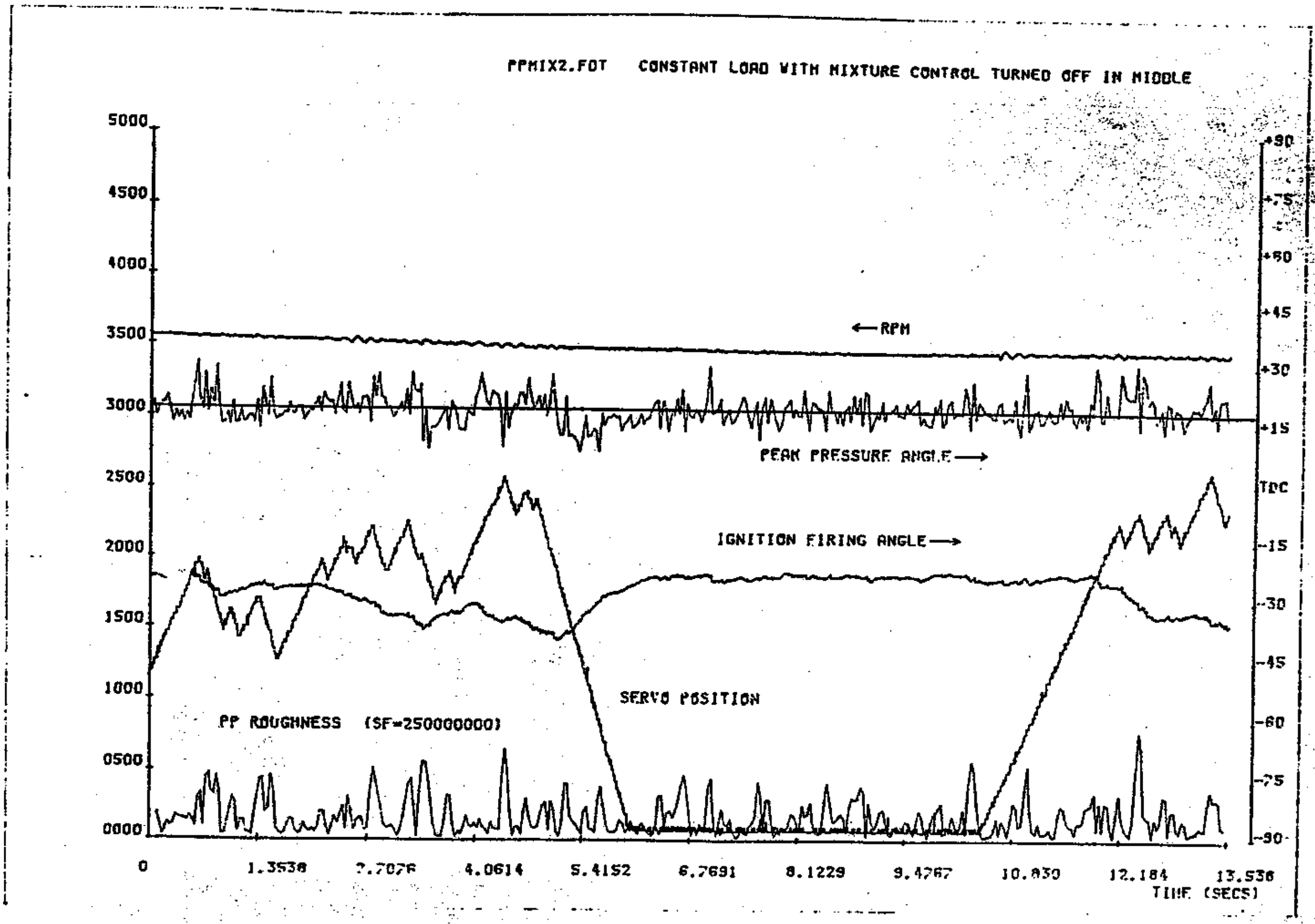


Fig. 8 - Effects of air bleed on ignition control system

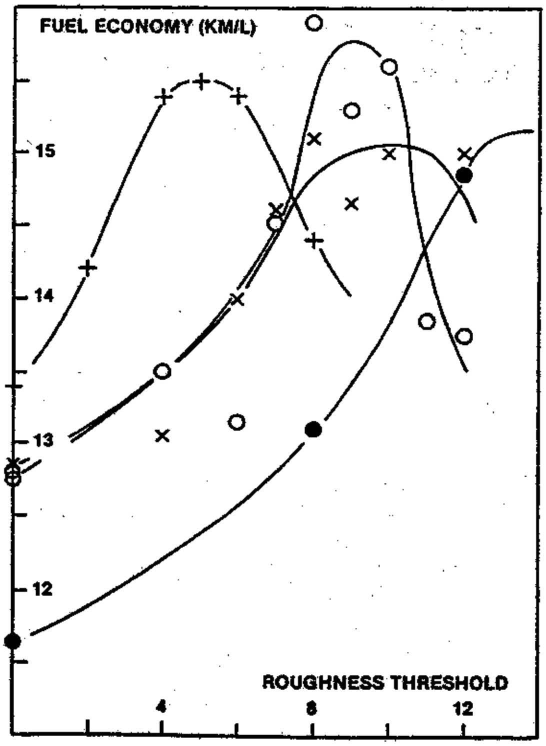


Fig. 9 - Fuel economy versus roughness threshold at various speeds (May 1981) (o 40 km/hr, x 50 km/hr, o 60 km/hr, + 80 km/hr)

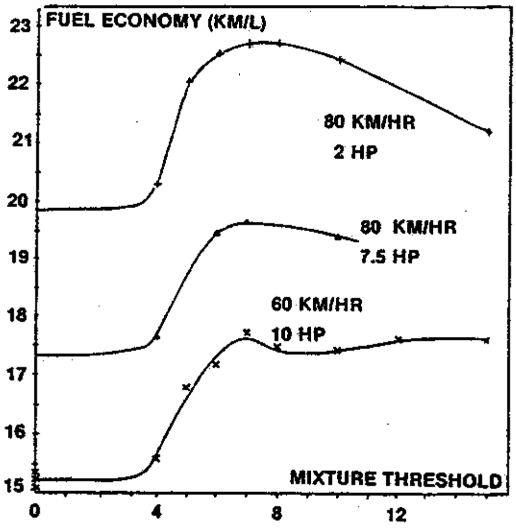


Fig. 10 - Fuel economy versus roughness threshold at various speeds and loads (October 1981)

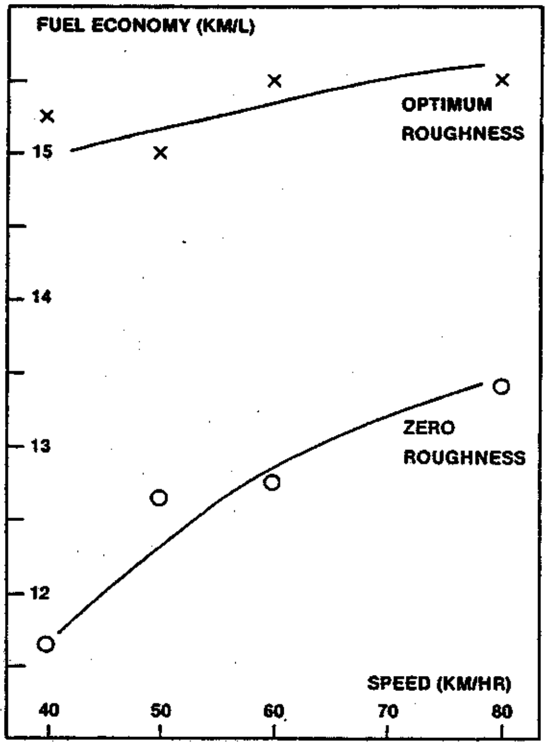


Fig. 11 - Fuel economy versus speed (from data of Fig. 9)

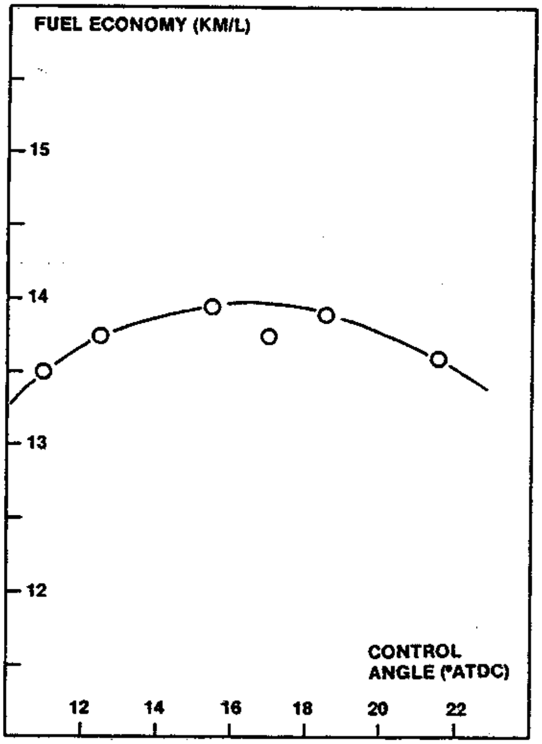


Fig. 13 - Fuel economy variation with pressure peak control angle (60 km/hr, load 150 to 160 mv

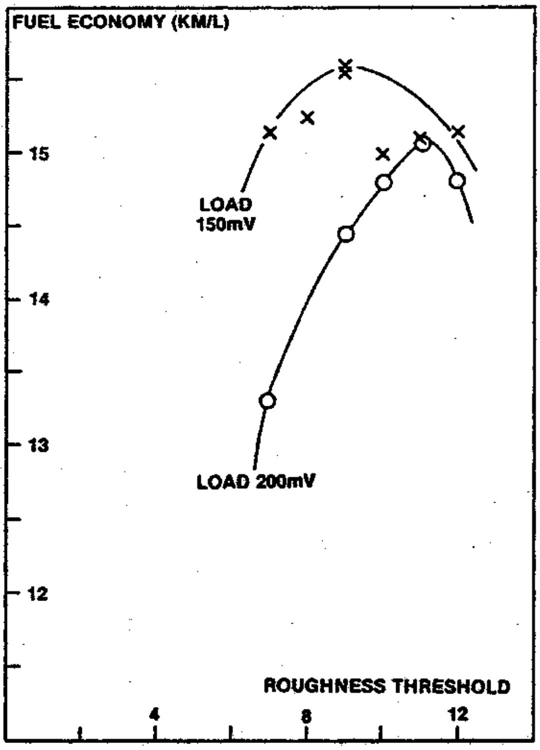


Fig. 12 - Fuel economy peak shift with engine load (60 km/hr, ignition control angle 18.5^{0} ATDC)