NEW ZEALAND ENERGY RESEARCH AND DEVELOPMENT COMMITTEE

INSTRUMENTATION OF CARS FOR FUEL ECONOMY

J E MORRIS*
Department of Physics
Victoria University of Wellington

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* The principal investigator, Dr J.E. Morris, who is now with Department of Electrical Engineering, South Dakota School of Mines and Technology, Rapid City, South Dakota 57701, USA, presented his final draft to the Committee in July 1981. This has subsequently been revised by his successor, Dr Robert Raine of the Department of Mechanical Engineering, University of Auckland. The opinions expressed are those of the authors and are not necessarily endorsed by the Committee.

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1. PREFACE

This report describes the development of an electronic system to control the air-fuel ratio (A/F) and ignition timing of an internal combustion engine to optimize fuel economy. The work has been supported since late 1979 by the New Zealand Energy Research and Development Committee.

The format of the report itself has presented a minor problem in that some of the material which it must contain (to be of use as a reference or digest of prior work for those continuing on the programme) is confidential. On the other hand, it is desirable to circulate the report as widely as possible to meet the obligations of both the University and NZERDC. This conflict has been resolved by the liberal use of appendices which contain most of the detailed information. The main report provides a brief general summary of the work and links the appendices. A specific appendix may or may not be accessible to the general public at a given time but it is expected that all will eventually become available as confidentiality constraints are lifted.

The first draft of this report was written in July 1981. Subsequent testing has clarified certain areas and necessitated modifications to the original draft. Sections 4.3(a), (b) and part of (d) have been rewritten in order to present the latest results. Appendices 29, 30, and 31 have been added, and Appendices 18, 19, 20 and 22 have been updated.

2. INTRODUCTION

2.1 Engine Control Systems

The development of electronic engine management systems has recently been reviewed elsewhere.(Ref.1) Emission controls in the USA began the process; early mechanical modifications to the engine paid a price in fuel consumption which was eased by early analogue electronic controls. As emission limits tightened, there was a move towards the greater control accuracy of digital techniques. The introduction of simultaneous fuel economy standards made digital processing essential and fortunately the microprocessor appeared on the scene to permit it to be done economically.

There are a wide variety of control systems but for the sake of a simplified presentation, the control function will be split into (a) mixture control and (b) ignition control. In (c) the fuel economy implications are examined.

(a) Mixture control: Emission levels as a function of air-fuel ratio are sketched in Fig.1(a) (Ref.2). The obvious way to reduce emissions is to move from the rich side of stoichiometric (where most New Zealand vehicles still operate) to lean operation. However, it is not possible to meet all the USA and Japanese emission constraints by this simple means. The modern solution is to use an expensive "3-way catalyst" which simultaneously oxidizes HC and CO emissions and reduces the NO_x. The catalyst, however, works only at stoichiometric (Fig.1(b), Ref.2) and requires the so-called "lambda-sensor" in the exhaust. This provides a lean/rich signal determined as the presence or absence of O_2 in the exhaust gases. The feedback (closed-loop) control system is shown diagrammatically in Fig. 2. In carburettor systems, first order mixture control is by the normal venturi effect with second order accomplished by an air bypass, float bowl pressure modulation or similar. Other systems are typified by the Bosch (Ref.3)/Volvo (Ref.4)/Nissan (Ref.5) fuel injection technique where air flow (measured by an air vane) determines first order injector on-time electronically, this setting being easily modified by the lambda input. Note that the catalyst action is destroyed by lead and that the removal of lead as an anti-knock agent has forced USA engines to less efficient low compression ratios. (The author does not know how lead substitutes affect it.) If the catalyst should become fouled, NO_x emissions (which are the ones which cause photochemical smog) increase beyond original levels. Note also that control does not begin until the lambda sensor reaches operating temperatures (i.e., not on short hops). The net effect of these and other points is that for New Zealand's emission control requirements, we are better to bypass this particular technology and take the lesser benefits available from the easier, cheaper and more reliable lean-burn approach.

(b) Ignition control: Ignition control is where the microprocessor becomes essential. For each combination of load (as represented by manifold vacuum) and rpm, there is an optimum ignition timing. A large number of these points are stored as a look-up table in a read only memory (ROM) and the appropriate instantaneous value calculated from the table by interpolation. Each map is generated by exhaustive testing of a specific engine/car combination and represents steady state optima only; transient controls must be handled by other techniques. This is an open loop system but a closed-loop override is sometimes added with a knock detector. The systems are more complex than appears here as there are also EGR tables, idle control devices, throttle transient detectors, etc. As vehicles age, the stored data should be changed.

(c) Fuel Economy: There is a world-wide drive for improved fuel economy which is producing smaller, lighter cars with many modifications to the traditional distributor, carburettor, etc. There is much talk of "a new generation of fuel-efficient cars". These claims must be kept in perspective. Fig. 3 (Ref.6) illustrates the point that the economy improvements being achieved with the sophisticated systems overseas are relative to a base of emission standards met by other means. Note that the baseline year here is 1978 where economy would be substantially below that of the standard pre-1970 engine with no emission constraints at all.

2.2 New Zealand's Requirements

In summary of 2.1 above, there are remarkable advances being made overseas in emission controls, with as little as possible loss of fuel economy. With less of a pollution problem and more of an energy one, New Zealand should aim for maximum fuel economy and look for emission reduction without sacrifice of the prime objective, rather then reverse those priorities. Maximum fuel economy is obtained at an A/F ratio on the lean side of stoichiometric. CO emissions are down here compared with conventional rich running, and so is HC provided the mixture is not too lean (in the misfire region). NO_x levels may be reduced depending on the precise A/F ratio. An example of these effects will be presented in Section 2.3.

New Zealand is also out of step with the "rest" of the world in that its fleet is roughly twice as old as those of the UK, Europe, Canada, USA and Australia. It is therefore more worthwhile for New Zealand motorists to install retrofit systems to improve fuel economy than for their counterparts in other countries. New Zealand, however, represents a relatively small market and it is clearly impossible to develop engine maps for every vehicle on the road. What is needed is a single system adaptable to all vehicles (possibly with small variations permitted). Such a system must operate in a feedback mode.

The control system which has been developed and which is described in this report has been aimed at these requirements: feedback control of both A/F ratio and ignition timing, A/F mixture to run lean, system to be adaptable to all New Zealand cars. Note that the system developed is incompatible with the fundamentally different closed-loop lambda control of mixture and with ROM ignition controllers. These would have to be bypassed in vehicles originally fitted with them. Despite the original objective of a retrofit system for New Zealand, OEM and export potential should not be ignored.

New Zealand also has a developing interest in alternative fuels. Although LPG and CNG are cheaper to run than petrol, it is still worthwhile to use them as economically as possible. Ignition timing should be adjusted in switching between gas and petrol; the feedback control would do this automatically. Similarly, alcohol fuels (M15, M85, ethanol) may demand modified mixture settings and timing. Again, the system provides these automatically. There is considerable interest in Brazil in utilizing A/F control with varying ethanol blends.

2.3 Leshner Fuel Mixture Control (Ref.8)

The mixture control system is based on a system developed by E. and M. Leshner (Ref.8). The concept is illustrated in Fig. 4. Although the flywheel damps out the rotational velocity fluctuations due to compression decelerations and combustion accelerations, these are still detectable electronically by processing the times between flywheel teeth. The control system gradually opens the bypass valve so that more of the air demanded by the engine at given load (manifold vacuum) and rpm is supplied by this route and less fuel is drawn in by the remaining flow past the venturi valve. Gradually the mixture is leaned out in this way until the electronics detects an "incipient" misfire i.e., the angular acceleration resulting from combustion is less than some threshold defined in some way. The valve then rapidly closes by some amount and starts to open again. This cycle is stated to take about 0.1 sec. to repeat (Ref.8) so that the driver is unaware of the fluctuations. The "lean limit" corresponds to the mixture of maximum fuel economy and ranges upwards from near stoichiometric (A/F=14.5) at idle according to rpm and load. (See Fig. 5, Ref.9, which incidentally also demonstrates the potential of good mixing). There are a number of adjustable parameters here (lean-out rate, enrich rate and increment, "misfire" threshold) which determine the effective A/F ratio. As these are varied A/F ratio increases with "correction" (i.e., enrichment) rate.

In this way Fig.6 (from Ref.8) shows economy and emissions as a function of A/F ratio. HC emissions are minimum at maximum economy, CO has also reached a minimum at this point and NO_x is decreasing. (NO_x emissions are maximum around stoichiometric where operating temperature is highest.) The result of an economy test (where the driver did not know the test was being conducted) is shown in Fig. 7 (from Ref. 8)

2.4 Powell Ignition Control

For feedback control it is necessary to test the effect of controller action to gauge its effect. Ideally one tests the parameter to be optimised, but fluid flow meters of sufficient accuracy and range are too expensive. It is, therefore, necessary to turn to some parameter known to correlate with maximum efficiency and preferably in as simple a way as possible. Maximum efficiency is related to maximum torque output and hence to the nature and timing of combustion. Timing of the combustion process has been correlated in two ways. Cook et al (Ref.10) noted that optimum ignition timing coincided with a maximum rate of rise of combustion pressure at 3°ATDC. Powell et al (Refs.11 & 12) state that the condition coincides with the peak of the combustion pressure occurring at 15-20°ATDC. The problem then resolves itself to one of economic measurement of the position of the pressure peak.

A piezo-electric ring replacing the spark plug washer provides just such a sensor (Refs. 12-15) shown in Fig. 8 (from Refs. 12-14) which gives an electrical signal following the pressure within the combustion chamber.

The sensor can also act as a knock detector with the characteristic knock frequency of the engine superimposed on the pressure signal. This can be isolated from the main signal by narrow band filtering to provide knock detection for spark retard override. The knock signal is detectable electronically before the driver is aware of its presence.

The control loop has been closed at Powell's Stanford laboratory on the single cylinder laboratory CFR engine only. The sensors have been used on the road there, but not as part of a control loop. (Ref.16)

3. PRELIMINARY SYSTEM DEVELOPMENT

3.1 Development Aids

Work on the development project splits naturally into two parts which will be covered separately in this and the following sections.

A review of microprocessors employed in engine management showed up the Motorola MC6801 as the only one designed specifically with that application in mind. It was expected that the timing requirements of the mixture control would demand the 6801's high speed processing and hardware multiply. The development of mixture and ignition controls was split and an MC6800 used for the easier ignition problem. Once both functioned the 6800 software (which is compatible with 6801) was to be merged with the 6801 system.

A 6801 development board was built and a 6800 D1 kit extended. (The 6801L1 chips actually failed due to an internal design fault but before the second died, the LILBUG monitor program was copied on to EPROM (Ref.17) and used with the otherwise identical 6803.) The next problem was to communicate with these to develop the appropriate software. A teletype is the conventional means, but instead a Commodore PET (purchased for this and other purposes) was software-configured as a flexible terminal/development system (Appendix 1). As an extension of this system, an EPROM programmer was built to operate from the PET (Appendix 2).

The other important development aid was the 1976 Marina 1300 van lent for the purpose by the NZ Motor Corporation. It was thought to be important to isolate the van's ignition system from the electronics, at least in the early stages. There was also some nervousness about the possibility of ignition spikes finding their way into the PET, with expensive consequences. As a result, two supplementary batteries were installed. One of these is designed to run the electronics and, apart from the earth connection, is isolated from the van's electrical system. The other is charged from the van's charging system through a diode. The only electronics it is connected to is the ignition interface (where the only IC is CMOS) through a switch on the dashboard; otherwise it supplies power to the PET through a 12v:230v inverter. The inverter delivers sufficient power for the PET and printer or disc drive, but not all three. A manifold vacuum gauge was installed; this is an industrial gauge for greater accuracy, reproducibility and ruggedness than the cheap automotive ones. Its original purpose was to assist in economy testing by enabling the driver to maintain constant load as well as speed. It is useful for this but also provides a ready indication of the functioning of the air-bypass. The inverter also powers a small oscilloscope for electronics testing on the road.

Fuel economy testing began immediately by logging mileage between tank refills. This is not practicable on the Marina, however, due to its tendency to overflow when full. Over longer periods one can distinguish a steady deterioration of economy, presumably as points wear, plugs foul, etc.

It was found necessary to keep the van running on the road regularly during development work. Most of this work involves testing at idle which causes carbon deposits to develop. After two weeks of only running stationary the van was misfiring badly and needed a lengthy highway run to restore 4-cylinder operation!

3.2 Ignition Control System

The 6800-based ignition control system is described in Appendix 3.

The software uses a reference marker from the flywheel and a pulse to indicate the occurrence of the cylinder pressure peak. These cause interrupts in the program which determines rpm and compares the actual timing of the pressure peak to the optimum at that rpm. There is a further interrupt generated by knock detection. The electronics is also included in Appendix 3 as is a program modification to extend the single piezo case to 4 piezos - one for each cylinder.

The output is simple: it is a pulse to drive the electronic ignition.

The system has run on the bench with simulated signals, but the electronics never handled those on the vehicle adequately. The main problem, however, was with the piezo signals and (as described in Appendix 12), the cause may well have been in the piezos themselves rather than the electronics. Nevertheless, the fact remains that the system was not tested on the road.

3.3 A/F Control System

The simple concept of misfire detection (Section 2.1 (a)) has been extended in the system actually developed. Appendix 4 examines the concept of "roughness" in some detail and discusses its quantification. Real data coming off the flywheel is extremely noisy and so some discussion of smoothing techniques is included in Appendix 5. (Both of these appendices contain material relevant to Section 4.) The air-bypass valve is a rotary type driven by a commercial servomotor (Appendix 6). The actual system (and software) is described in Appendix 7 but consists essentially of a TDC marker (the same one as for 3.2 above), a sensor to pick up the passage of flywheel teeth and the servo control signal as output.

The controller was tested by Beca Carter Hollings and Ferner at the A.A. dynamometer, Auckland, and gave 12.8% fuel economy at 80 km/hr (cruise) and 3.9% at 50 km/hr.

At this stage of the development, a provisional patent specification was filed (Appendix 8).

4. PROTOTYPE SYSTEM

4.1 System Design

The first stage described in the preceding section can be regarded as a familiarisation exercise. At this point, the approaches taken to many parts of the system were reconsidered and in several cases changed.

Flywheel timing as performed in the A/F controller is clearly too demanding on processor time and for the system to function at high rpm it was necessary to severely curtail the number of teeth considered. Fortunately there are several other approaches to determining roughness (Appendix 4) and the simplest of these in hardware terms, based on the TDC marker, was chosen and functional software written. This was extended to two markers to permit individual cylinder effects to be determined. A simple smoothing routine (Appendix 5) is switch selectable. Magnetic sensors were used for a time (Appendix 9), but were finally discarded in favour of a simple optical sensor which is more reliable at low speeds. An ignition interface was developed in the very early stages to drive commercial electronic ignition from a microprocessor signal. (This has performed reliably now for 18 months.) The interface also has a points input so that the system reverts to normal operation if the microprocessor fails or is removed. Essentially the same system is used in the current prototype (Appendix 11) except an electronic ignition has been incorporated to replace the commercial one. Similarly the same types of valve and servomotor have been used (Appendix 6) but built into a separate box with its own air cleaner.

Early problems with the piezo-electric sensors themselves have been resolved (Appendix 12) and a simple reliable design developed. A variety of alternative piezo-electric sensors under consideration are also described in Appendix 12. One of the major questions to which it has been difficult to find a definitive answer is: How universal is a single optimum pressure peak position and how broad is the economy/peak-position curve? In other words, can a single system with no adjustable parameters be effective on most of the common New Zealand cars? The question is discussed in Appendix 13 but no definitive conclusion is reached due to insufficient data. In fact, the appropriate experiments on New Zealand models have probably never been done. A variety of approaches have been taken to the interfacing problem of generating a reliable pulse at the pressure peak time without random error pulses. These are described in Appendix 14. The final design is based on a zero-crossing technique but bears little other similarity to that described in Appendix 3.

In the course of planning the current prototype development, it was apparent that the 6803 was over specified. It was retained, however, for the investment in familiarity and experience with the device and as an insurance against future escalations in the processing power required. The 6803 system is covered in Appendix 15-17. The interrupt driven software is described in Appendix 15 in the form of pseudo-PASCAL routines with associated machine-code listings. Only single piezo sensing is catered for, but the possible extension to more is easily included. Four roughness algorithms are included within the software and are switch selectable. This material was actually developed using a modified 6800 assembler/ editor provided by the Computer Services Centre, V.U.W (Ref.18), which resides in

EPROM on a fairly standard development board (Appendix 16). The modified board design for use on the vehicle is contained in Appendix 17 and the overall system assembly on the Marina is illustrated in Fig. 9(a). Fig. 9(b) shows the modification for units installed in other vehicles. Fig. 9(a) also includes data acquisition facilities (Appendices 18-21) and a diagnostic link to the PET configured as a terminal (Appendix 22). The foreground software task of the 6803 is, in fact, to output diagnostic data to the PET display. The CPU is involved in interrupt routines and control functions for only about 20% of its time (Appendix 15).

4.2 Test Systems

It was decided that there were three distinct requirements for analysis of system performance. When the work is finished the only result of interest will be the change in fuel economy. This must be measured according to some recognised standard, e.g. the New Zealand Standard Drive Cycle (Ref.19). The program for this is not yet written, but general algorithms have been worked out and are described in Appendix 21.

The main task is to provide an aid to the driver in keeping to the very rigorous speed-time profile. The PET buzzer (Appendix 1) provides start, stop, ready, too fast, too slow, abort and gear shift signals while the program accumulates total fuel, the amount used in each section (for comparisons between runs of specific parts of the cycle) and instantaneous deviations from the ideal speed for a "quality control" check on each drive. Only mileage and fuel flow sensor inputs are required.

It is not generally possible to exactly reproduce driving conditions on the public road over sufficient distances to be useful. The alternative approach is to build up a set of "with and without" or "before and after" data over many runs over the same route under similar conditions. This is the purpose of the "normal" drive software covered in Appendix 19. Again, only fuel flow and mileage information is used. However, the PET is so lightly loaded in this case that it can put a speed profile of the run out on the screen along with mileage and fuel consumption information. These data are then printed out at the end of the run with average fuel consumption. The latter figure may then be compared with others for the same route displaying a similar speed profile, and taken at the same time of day (for similar engine temperatures). This system works well but requires a significant number of runs or distance before quotable data is obtained.

The third set of software (Appendix 20) is aimed solely at diagnostic purposes. The idea is to see what happens on the engine, how the electronics responds and how the engine then responds to control during transients. In the early stages, the system has been very useful in simply understanding how the basic system works. The concept is to grab data about every event of interest over a short period of time and this is done by recording the time at which each event occurs. The program accumulates data identifying events and times of occurrence until the reserved memory is full. These data are then stored on cassette (after visual inspection to ensure quality data if desired) for later analysis in the laboratory (by a second PET) and graphical output on a Watanabe MIPLOT digital plotter.

The hardware associated with these three programs consists of an Ono Sokki fuel flow meter with 0.1 ml resolution, a simple distance-travelled sensor attached to the driveshaft and an interface to send these and miscellaneous signals from the control electronics to the USER port of the PET. The interface (Appendix 18) converts the flowmeter signals to two lines representing forward and reverse fuel flow of approximately 0.1 mls per pulse. Otherwise each input responds to a positive edge and puts up an identification code to the PET.

4.3 System Performance

(a) Chassis Dynomometer Tests:

Dynomometer tests were carried out with the van in the Thermodynamic Laboratory, Department of Mechanical Engineering, University of Auckland. The results of the Auckland tests (October 1981) are presented in Appendix 29. The vehicle was set up at the desired speed and the consumption determined by the "normal drive" program.

Fig. 10 shows the mixture control results. The maximum fuel economy improvement ranges between 13% and 16% for the loads and speeds tested. The threshold values for both the onset of improvement and maximum improvement are the same in each test case.

Fig. 11 shows the ignition control results. No peak is discernible. An ignition hardware fault was suspected at the time. Other possible factors are: at the speed and load chosen, ignition angle is not critical; there is insufficient information to properly determine the correct angle from only one piezoelectric sensor; there is an error in the microprocessor's calculation of angle due to the incorrect assumption that the angular velocity of the crankshaft is constant. These areas require further research.

(b) Drive Cycle Testing:

The New Zealand Standard Drive Cycle test was performed at Auckland in October 1981. The results are presented in detail in Appendix 29. The drive cycle testing arrangement is being developed by the

Mechanical Engineering Department,
University of Auckland.

Fig. 12 shows a sample drive cycle. This was used to compare a normal car to a mixture controlled system. A threshold of 6 was used for the mixture control (cf. Fig. 10). The ignition control was not fully tested on the drive cycle as the results in 4.3(a) implied that no conclusive saving would be detected.

Fig.13 presents the drive cycle test results. There was a 5.8% improvement in fuel economy for the mixture controlled system. The repeatability between test runs is very good.

Two runs were performed using both mixture and ignition (controlled to 18^o ATDC) control. These produced results in the range obtained for the normal car. Possible reasons for this are given in Section 4.3(a).

(c) Lean-Burn Temperatures:
A common reaction in New Zealand to the idea of lean mixture operation is that this leads to burned valves. It must be emphasised that the traditional engine runs on the rich side of stoichiometric, i.e., of the point of maximum combustion temperature where the chance of burning valves is greatest. If the mixture control takes A/F ratio over the peak as expected, then valve temperatures may well be less than normal.

To make the point, a thermocouple was inserted into the exhaust manifold through a hole drilled in a small bolt threaded into the manifold itself. Temperature readings with various roughness thresholds (i.e., mixtures) were taken in sequence as shown in Fig. 14. As well as constant speed, manifold vacuum was maintained as near constant as possible on the road. Any consistent trend is certainly less than the random fluctuation. However, it is disturbing that the expected stoichiometric peak does not show up, unless it corresponds to the solitary batch of points at threshold 8. It may be worthwhile trying this test again with the thermocouple either attached to the valve itself or beside the seat.

(d) Fast Data Results:
The fast data acquisition system has been useful in demonstrating the effectiveness or otherwise of the control program under various road conditions. Appendix 30 contains half-size photo-reductions of the complete set of fast data graphs and gives observations on each. Some examples, with brief comments, are presented here:-

Fig. 15: With fixed ignition timing the position of the combustion peak changes with load. Clearly, more advance is needed here at light load. On overrun the combustion peak effectively vanishes leaving the compression peak at TDC.

Fig. 16: With peak position control in place, a load change now produces a change in ignition timing.

Fig. 17: Apart from giving an indication of ignition controller response times, Fig. 17 is designed to show (by the extreme case of no-load/overrun), the existence of the minimum advance curve. When peak position moves to TDC an overrun, the ignition timing tends to retard but is limited by this stop.

Fig. 18: For this case the control angle was switched between settings. Again one can see finite response times.

Fig. 19: Two points are illustrated here. By changing the roughness setting from zero to some finite value, the servo is caused to open. The first point of interest is the rate of servo opening and, when threshold is returned to zero, the faster rate of closure. As the servo opens and the mixture leans out, the ignition timing advances to maintain the peak position with the slower combustion. In addition, the dispersion in the pressure peak position increases. Fuel flow is also shown, but little can be taken from this particular trace.

Fig. 20(a) & (b): This shows data from rapid uphill acceleration (including gear changes where peak pressure position goes to TDC) from rest. The real reason for its inclusion, however, is to demonstrate the scale-changing capability of the data analysis system.

(e) Driveability:
Driveability depends upon control parameter settings but appears to be satisfactory (i.e., no detectable deficiencies where economy peaks), as has been claimed by others. If one tries to run the engine too lean, detectable surging results and economy deteriorates. It is significant that drivers not involved in the development felt no obvious effect of the controller during demonstrations (Auckland, July 1981).

5. CONCLUSIONS

The main point to be drawn from the work to this point is that a significant improvement in fuel economy can be achieved by a control system of the type developed. It is clear, however, that considerably more work needs to be done. One area mentioned above is the need for more systematic fuel economy testing against speed and load as control parameters are varied for optimization. This is only a small part of the continuing research programme which is outlined in more detail in Appendix 23. Included there are several minor variations of the system as developed. However, there is a substantially different concept which needs to be checked out (Appendix 24). A more economic air bypass system must be developed (Appendix 25).

Throughout the course of the development, the ultimate objective of a cheap retrofit system suitable for installation by the home handyman has been kept in mind. In retrospect this was probably a mistake, in that demonstration of system feasibility could have been achieved more rapidly by the use of commercial instrumentation. However, costs and commercial feasibility have been kept in mind throughout. Current cost estimates and some thoughts on commercial development are contained in Appendix 26. One of the elements in consideration of a commercial system is the universality of various designs - control parameters, sensors and hardware mounting. Some relevant data on common New Zealand cars are tabulated in Appendix 27.

As mentioned above, the 6803 CPU is over-specified. The 6805 has been considered to be a very suitable replacement (although others can do the job), and preliminary steps toward a 6805 development system are described in Appendix 28. In the light of results obtained in the final months of the project, Appendix 31, written by Hugh Anderson, outlines the proposed final prototype system.

6. ACKNOWLEDGEMENTS

Acknowledgement must be made of those who have assisted the project in many varied ways. First, the New Zealand Energy Research and Development Committee is thanked for its continuing support (not only financial) and patience in the face of delays, missed deadlines and budget over-runs. Special thanks for assistance go to Dr G.S. Harris, Dr L. Arnoux, and to the Chairmen, Dr C.J. Maiden and Professor R.F. Meyer.

The ultimate objective of this work has always been the wide-scale adoption of the control system by the driving public, which cannot happen without commercial exploitation. The question of commercial commitment to the project's concept has been vital at various points but never more so than in the initial stages. For this reason the support of the following cannot be over-emphasised:

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- Autopoint who provided garage space and technical assistance. Mr Mike Quinn of Turnbull & Jones lent the inverter installed in the van.

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Amongst those mentioned above, Roy and Hugh can be singled out for a special vote of thanks. They have contributed significantly to this report, entering the full text into the VUW Burroughs computer for editing, and writing appendices 14 to 17 and 18 to 22 respectively. The project has also had the full co-operation of the University's Computer Services Centre, especially from Tim Naylor whose assistance has been invaluable.

From time to time the facilities of the Department of Mechanical Engineering at the University of Auckland have been used. Staff of that Department, the Engineering School Workshops and the Thermodynamics Laboratory have offered support and much appreciated encouragement when needed. With apologies for not including a more comprehensive list, particular appreciation is recorded here for the assistance of Mr John Stephenson for providing facilities, Mr Keith Jones for assistance with spark plugs, and Mr Stephen Elder for assistance with vehicle dynamometer tests. From the USA the Ford Motor Company has donated components and Dave Powell, Mike and Erv Leshner, Bill Wolber and others contributed information.

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17. With permission of V.S.I. Electronics, Motorola's New Zealand agents.
18. Copyright, Tim Naylor, Computer Services Centre, Victoria University of Wellington, Private Bag, Wellington.
19. SANZ, New Zealand Standard, NZS 5420:1980, "Methods of Test for Petrol Consumption of Passenger Cars", 1980.
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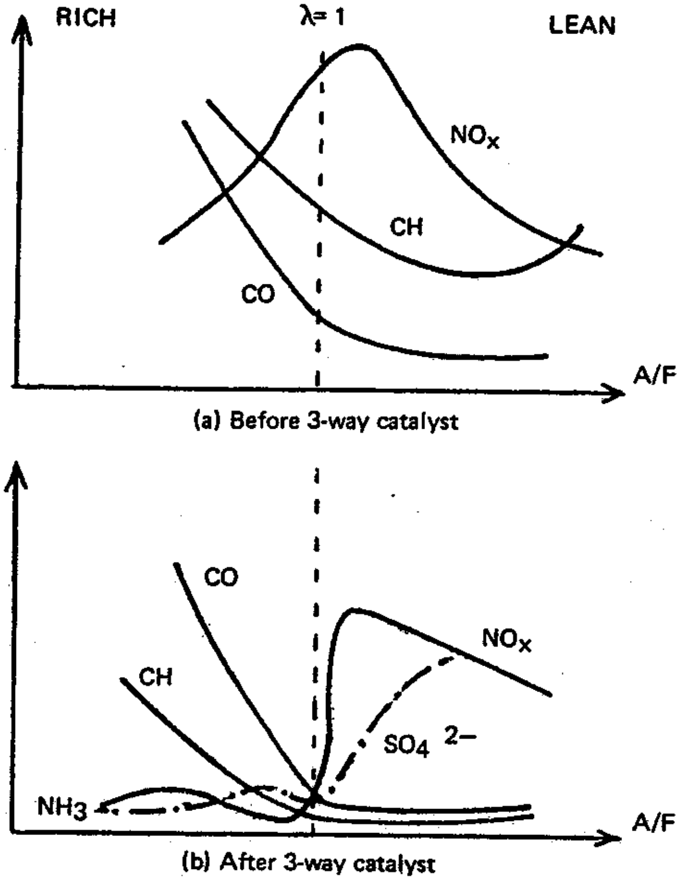


Fig. 1 - Relative emission levels - variation with fuel mixture (Ref. 2)

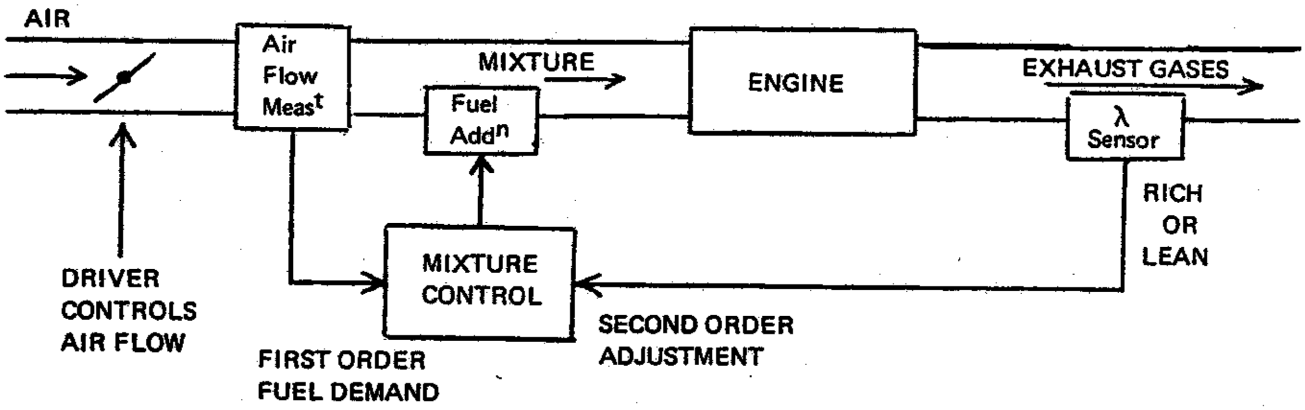


Fig. 2 - Closed loop mixture control

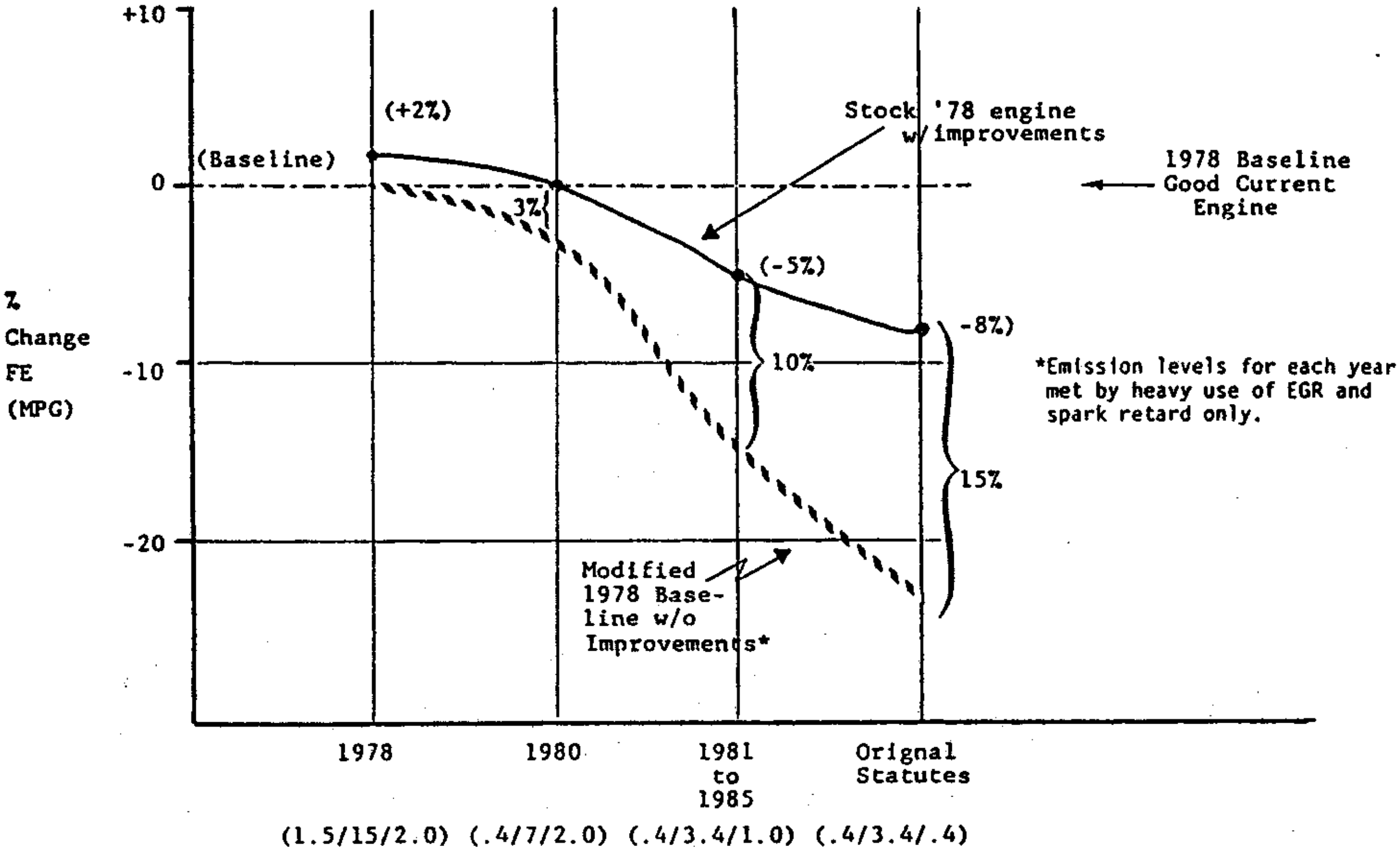


Fig. 3 - Projected MPG improvements. Combined A/F, EGR, spark advance, 3-way catalyst, Ø ≅ 1 (Ref. 6)

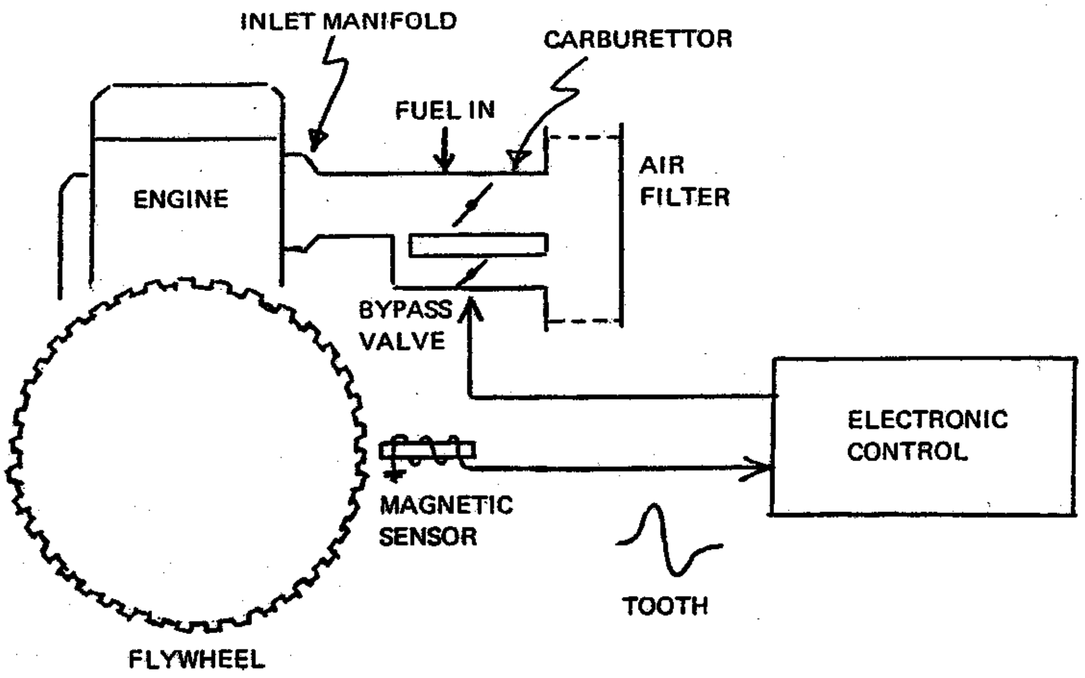


Fig. 4 - Leshner mixture control

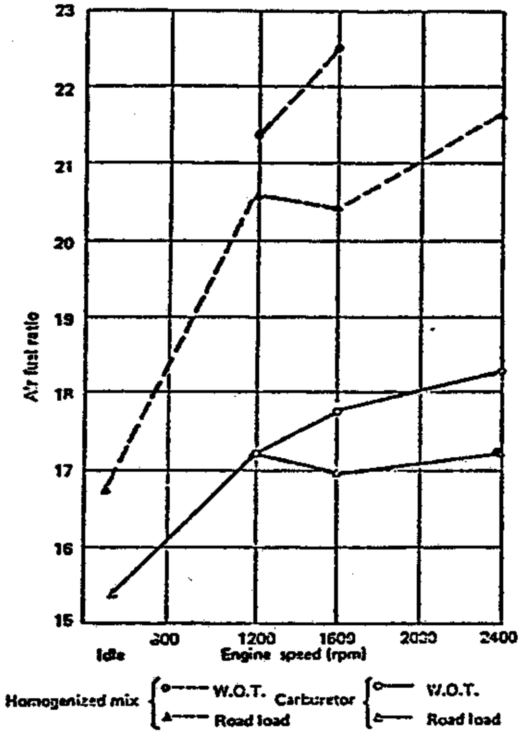


Fig. 5 - Misfire lean limit(4) - Carburettor - Homogenized mixture tank (Ref. 9)

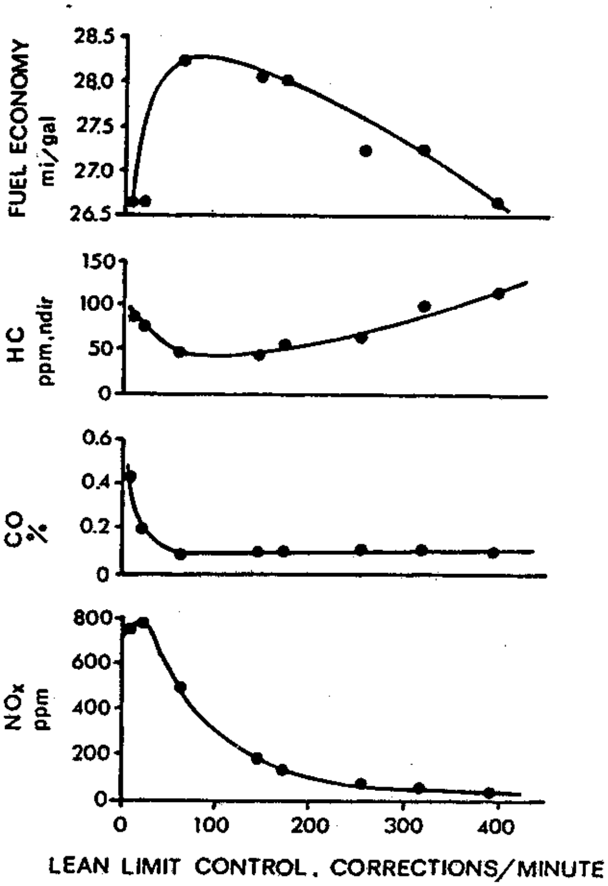
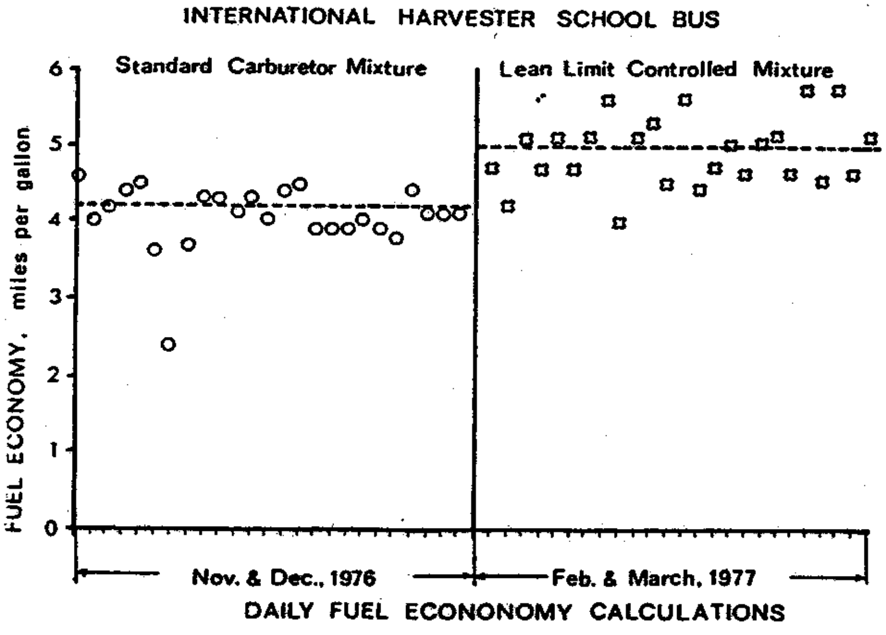


Fig. 6 - Fuel economy and emissions as a function of lean limit controller mixture bias. 1976 AMC Gremlin 232 C.I.D. at 40 mph, 5 hp dyno load, 6 deg basic timing (Ref. 8)



ig. 7 - Daily fuel economy calculations comparing standard carburettor mixture with lean limit controlled mixture. International Harvester 345 C.I.D. gasoline school bus (Ref. 8)

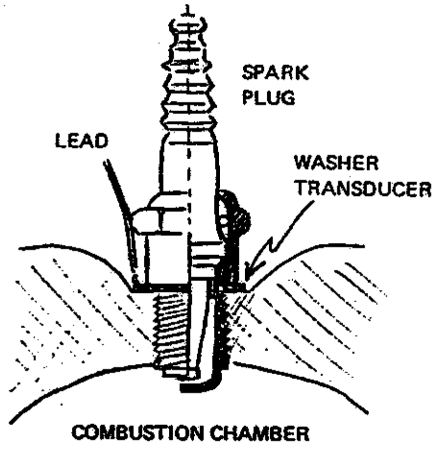
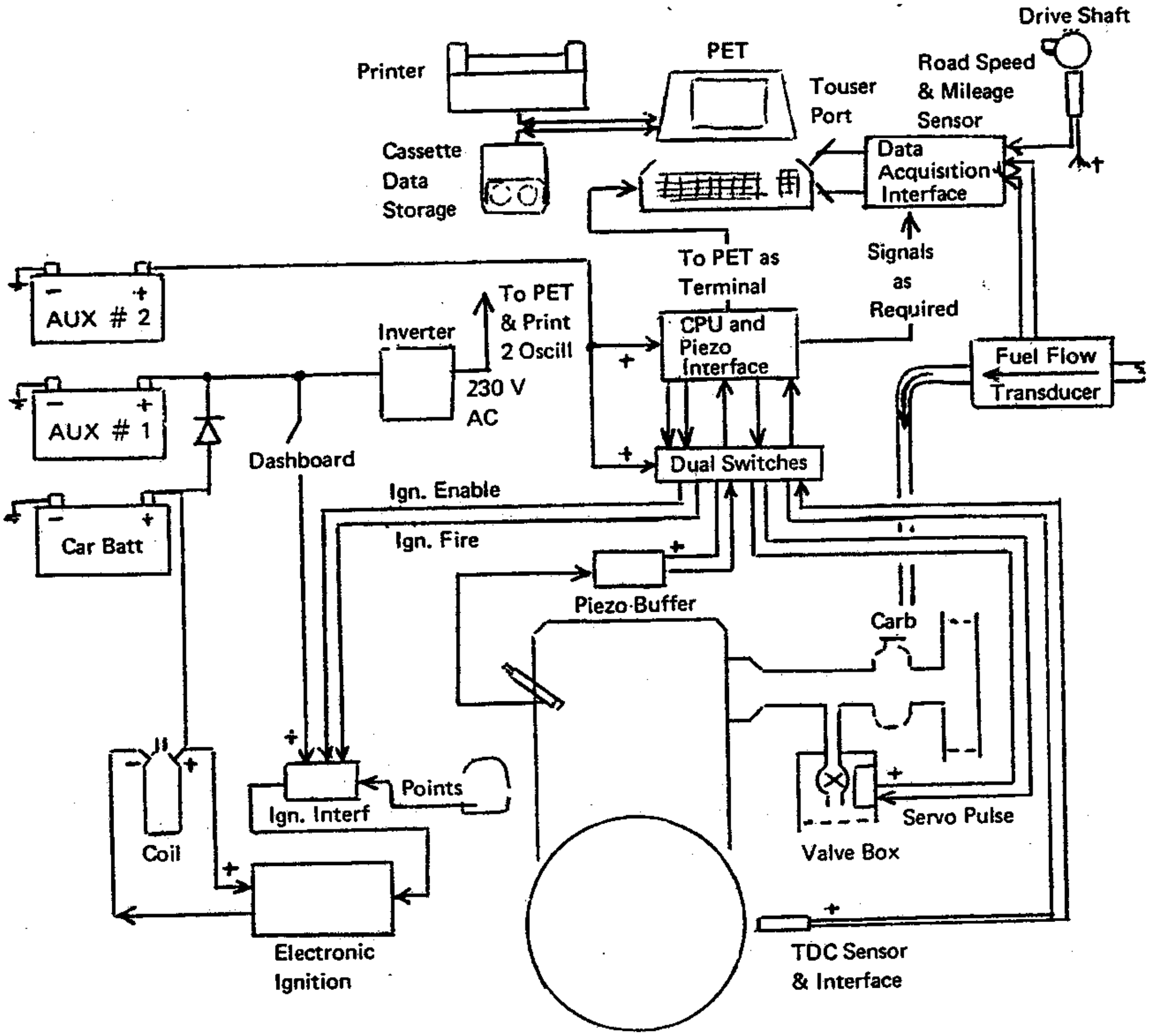
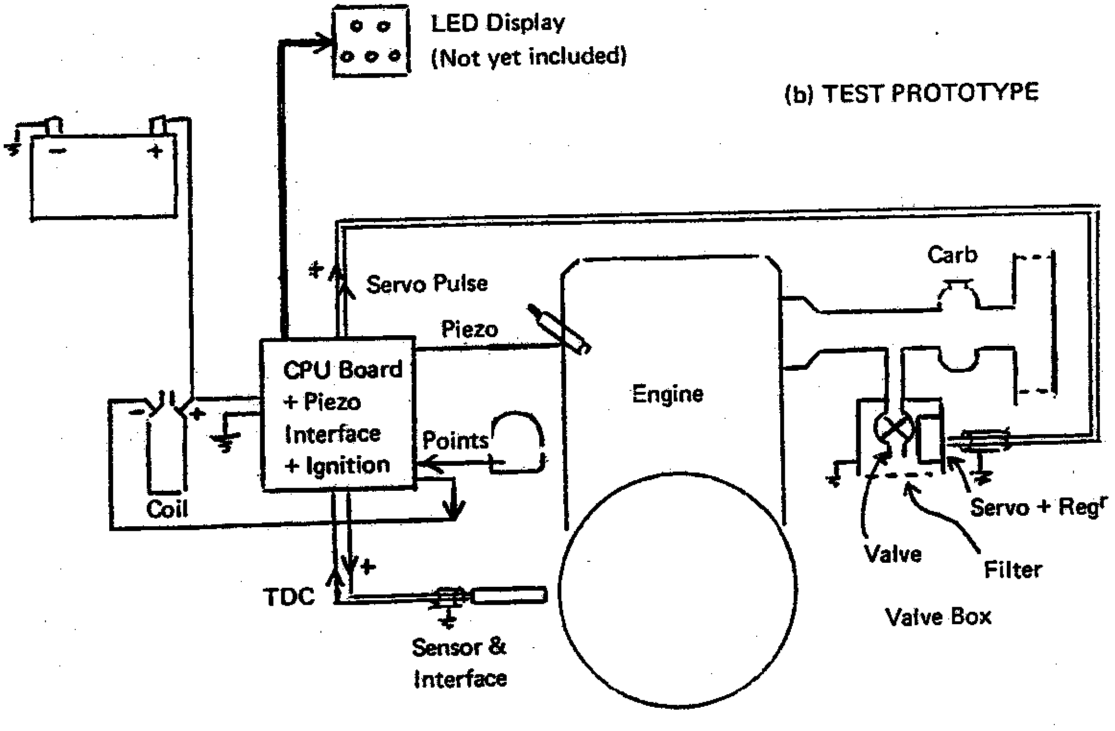


Fig. 8 - Piezo transducer (Refs. 12-14)



(a) MARINA SYSTEM LAYOUT



(b) TEST PROTOTYPE

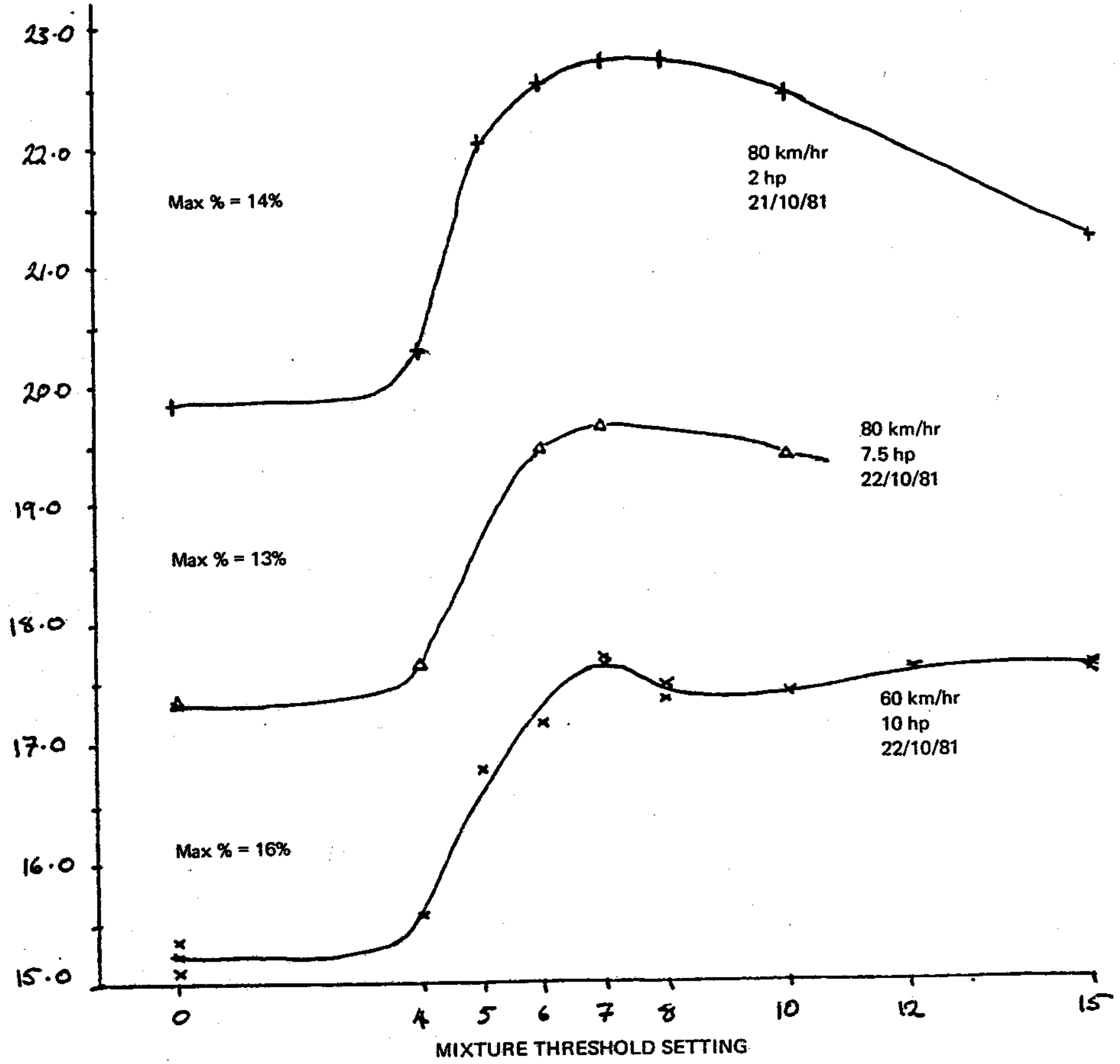


Fig. 10 - Dynamometer tests - fuel consumption versus roughness threshold setting with mixture control only; constant speed load

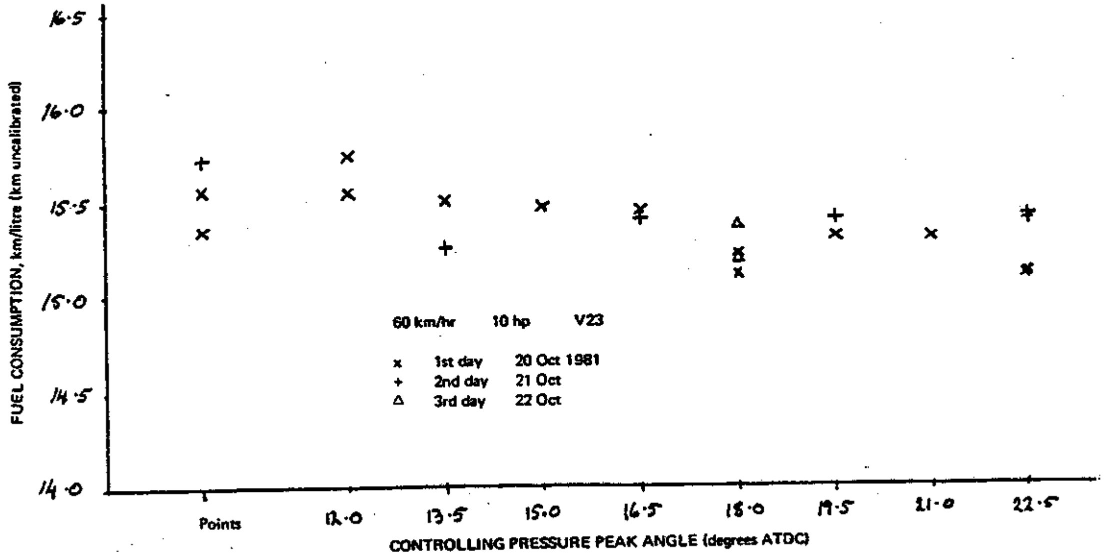


Fig. 11 - Dynomometer tests - fuel consumption versus controlling pressure peak angle with ignition control only.

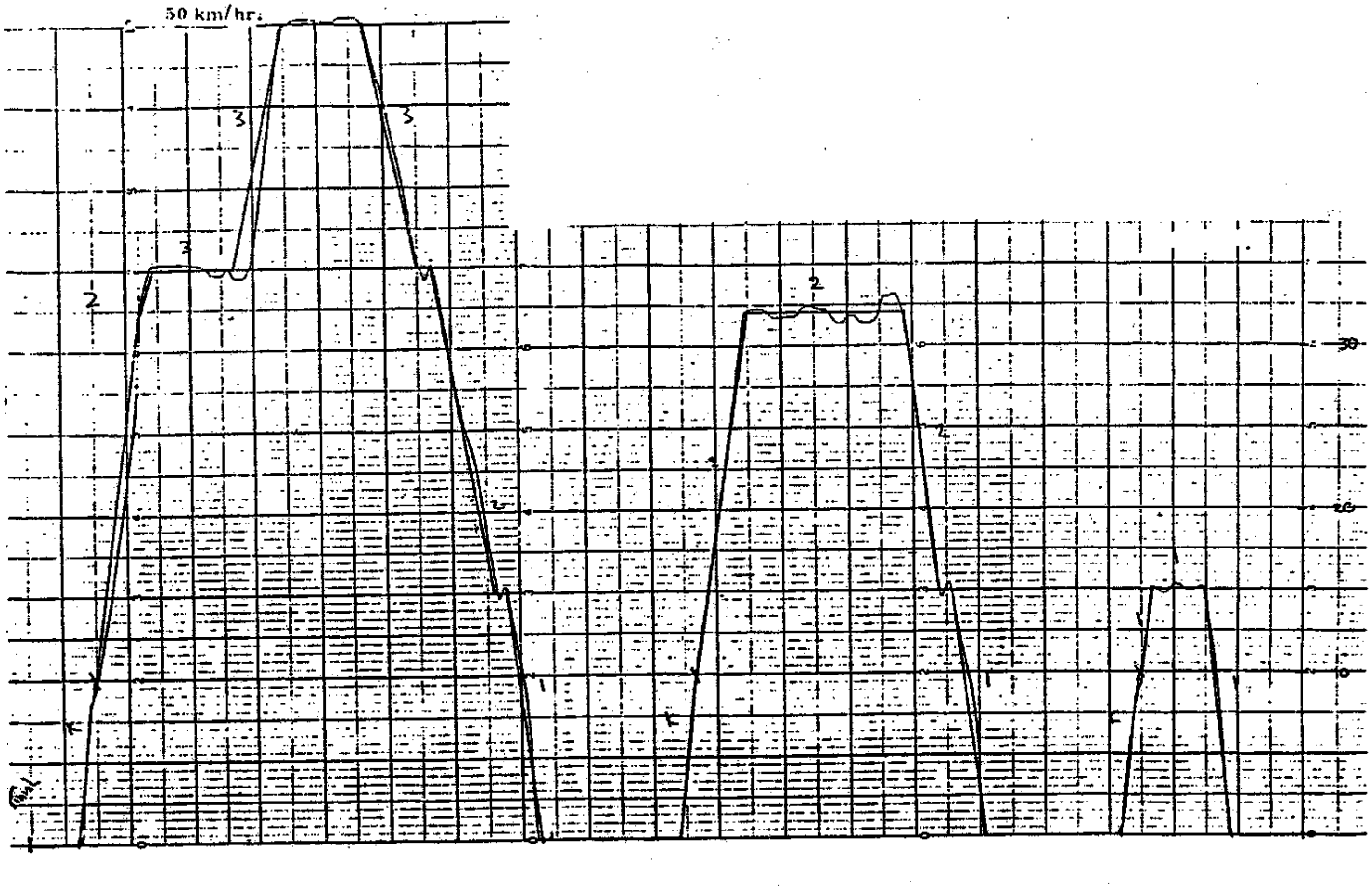


Fig. 12 - Sample drive cycle on the dynomometer.
Auckland 23/10/81, Mixture control V23 T=6

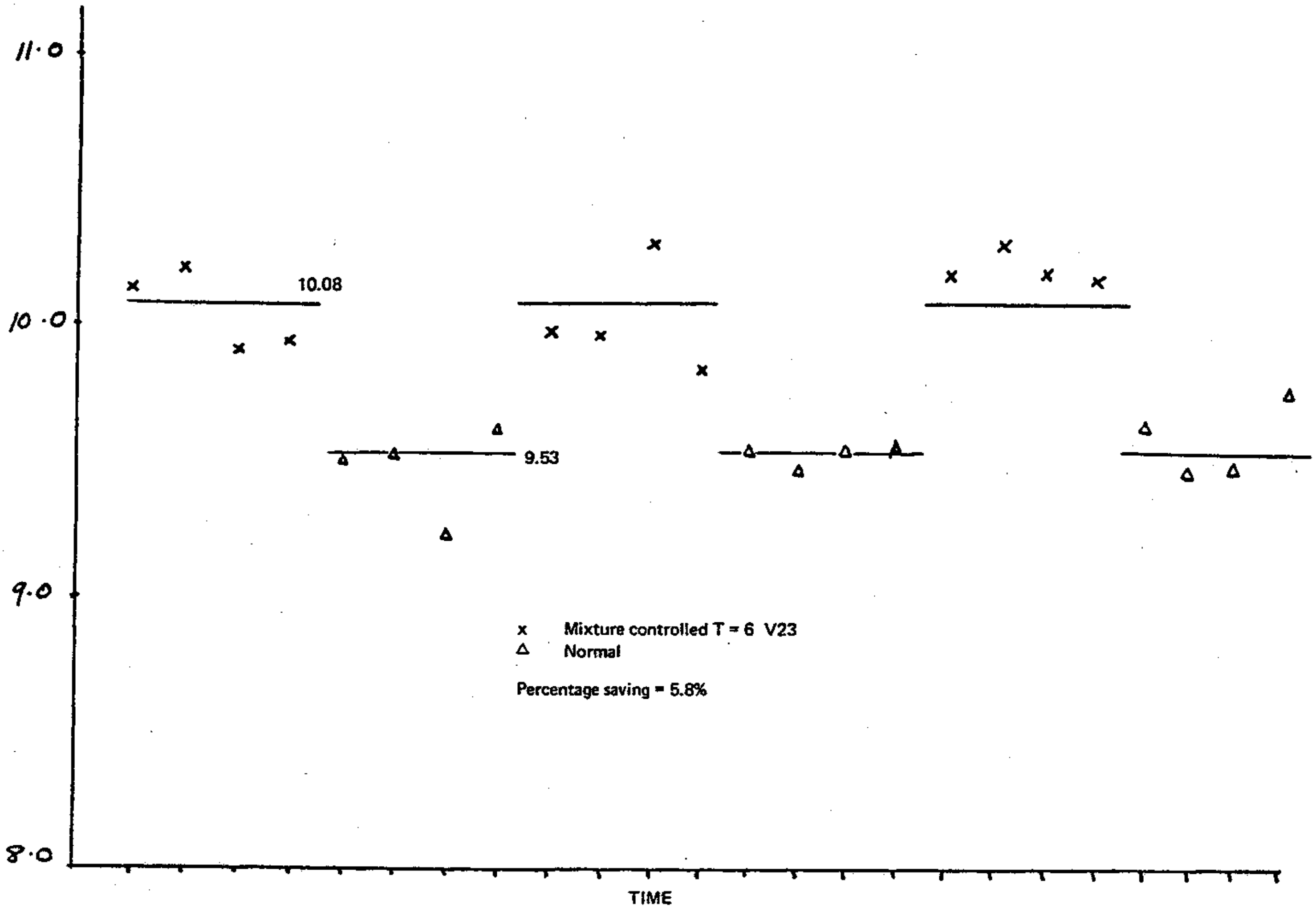


Fig. 13 - Drive cycle results for Marina with mixture control compared to normal, 22nd October 1981

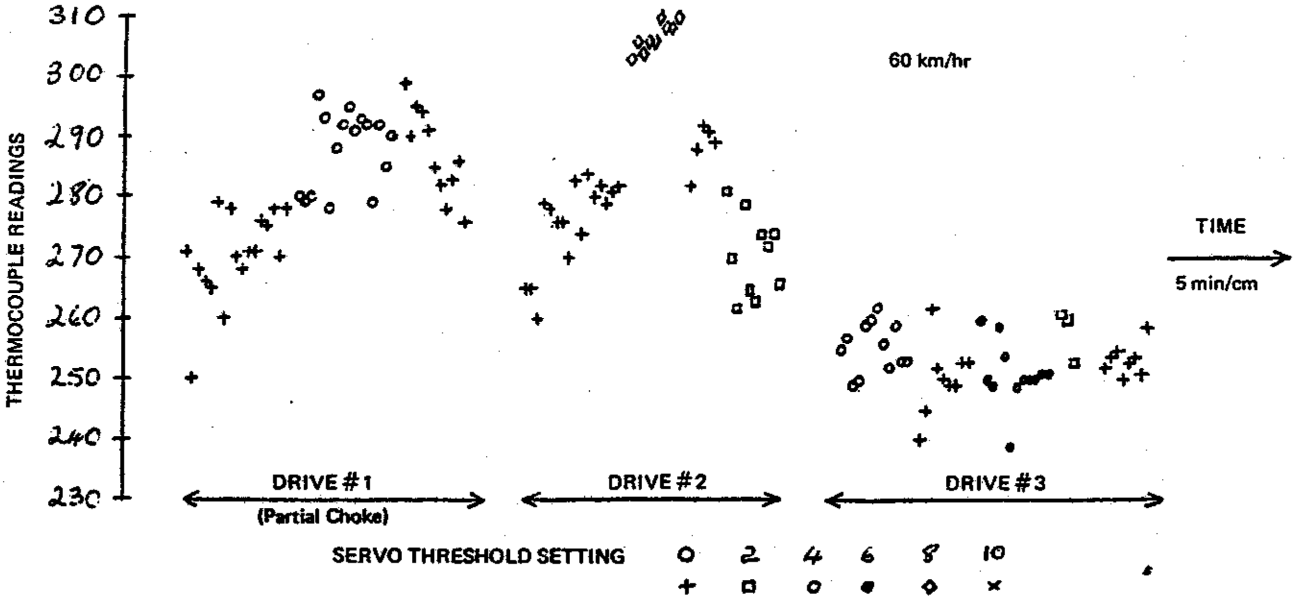


Fig. 14 - Exhaust gas thermocouple readings vs. mixture control setting

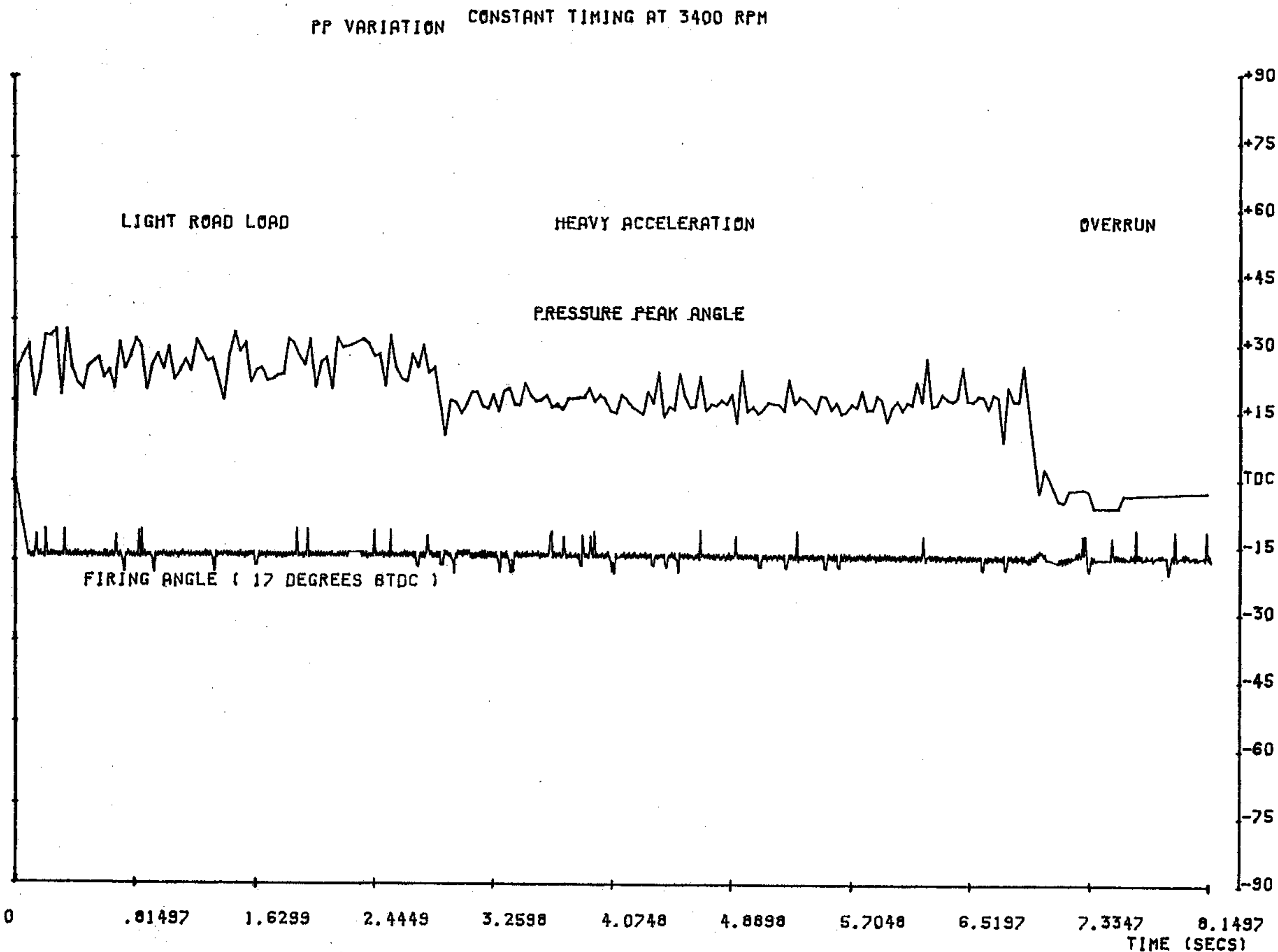


Fig. 15 - Variation of pressure peak position with engine load

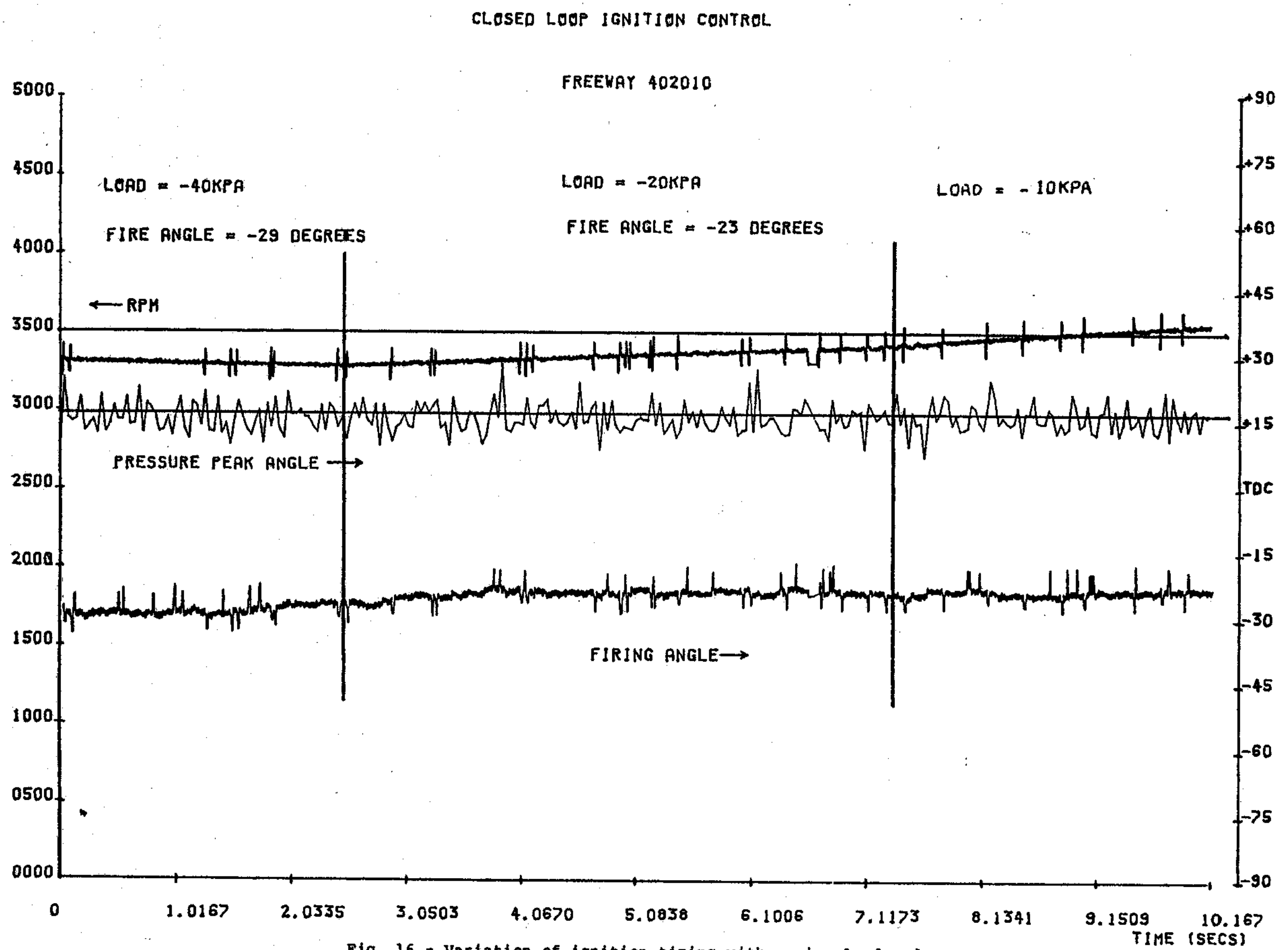


Fig. 16 - Variation of ignition timing with engine load under peak position control

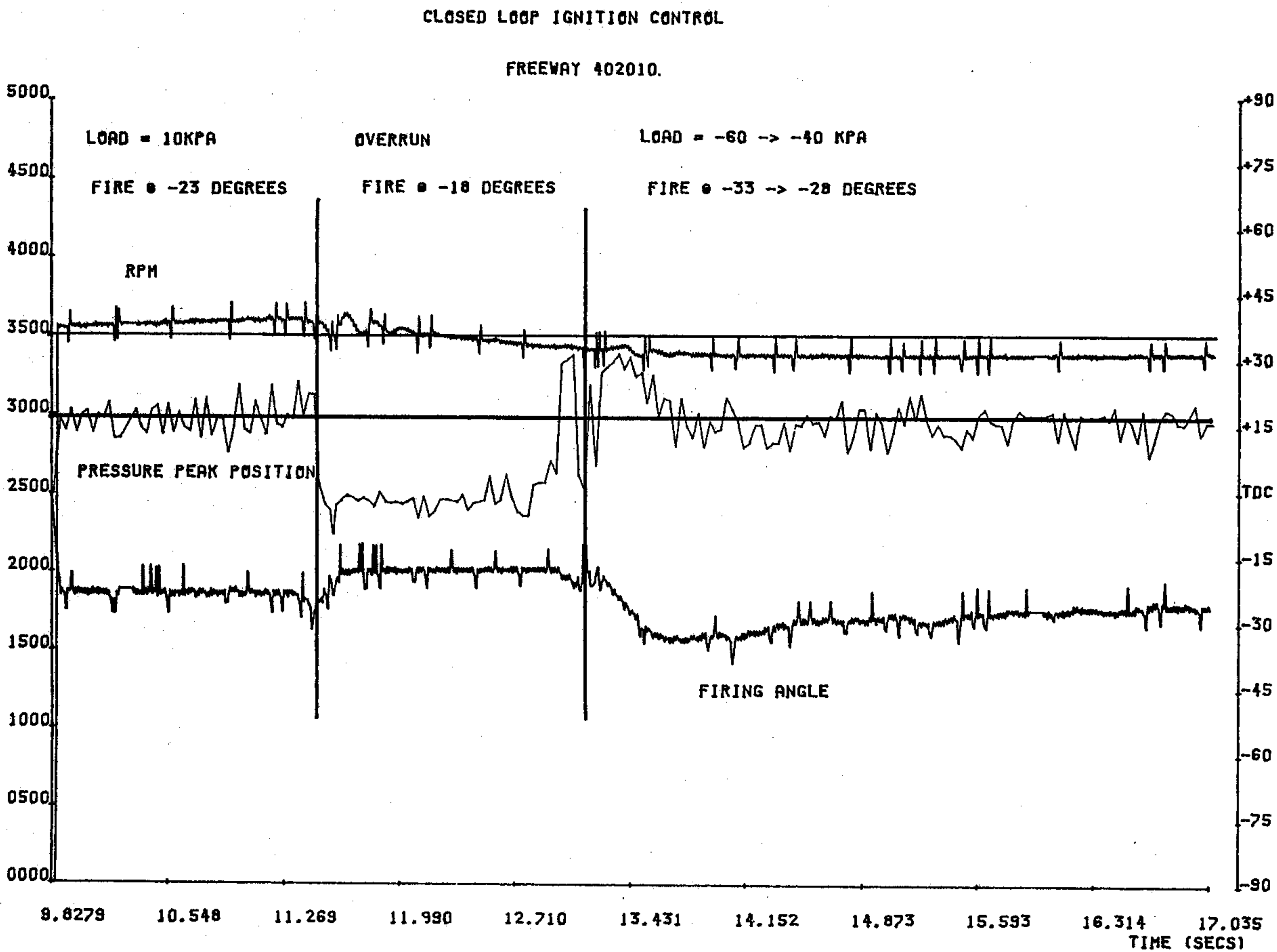


Fig. 17 - Effect of no engine load

FREEWAY 3000RPM PP CONTROL TEST.

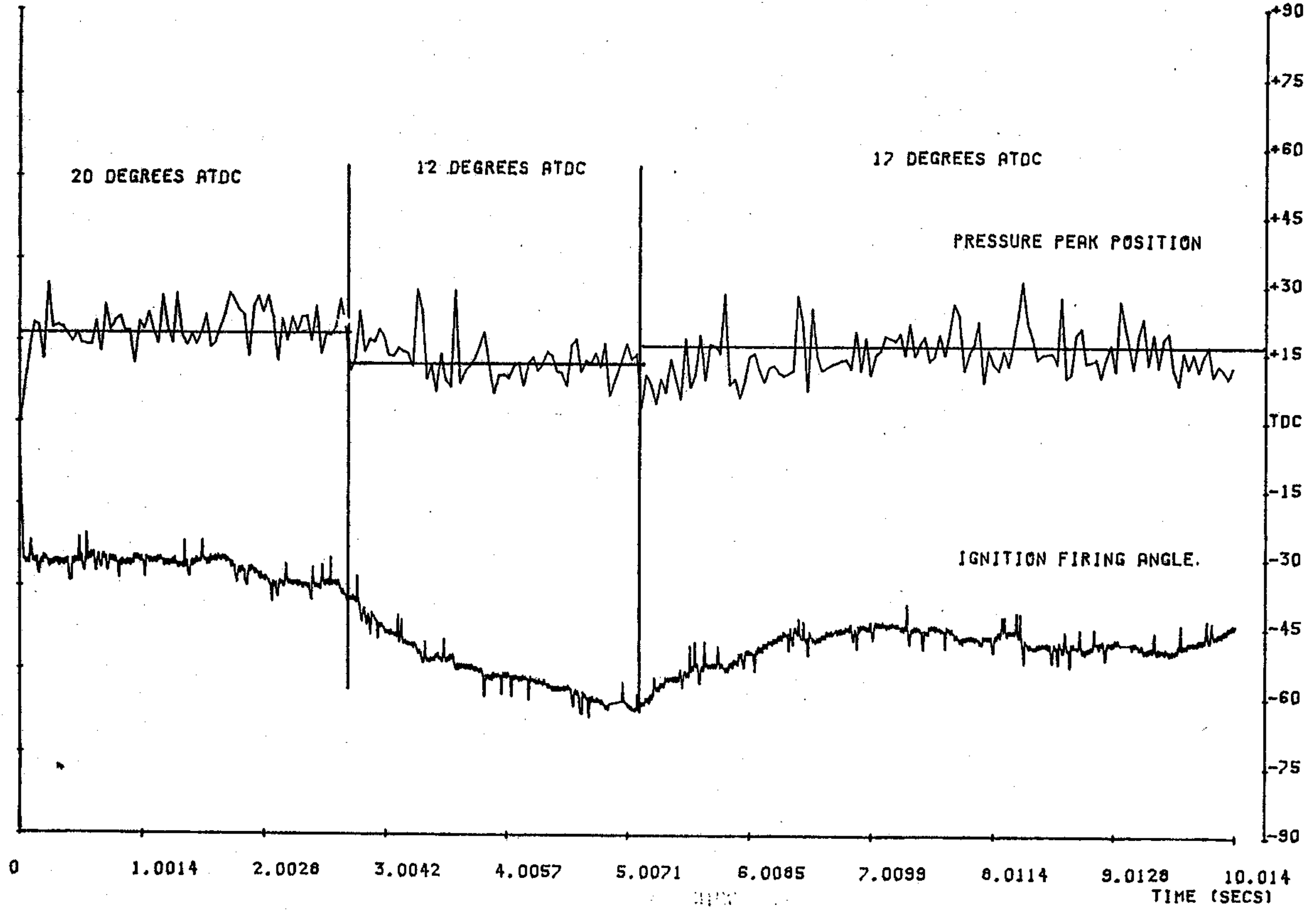


Fig. 18 - Ignition response to control angle changes

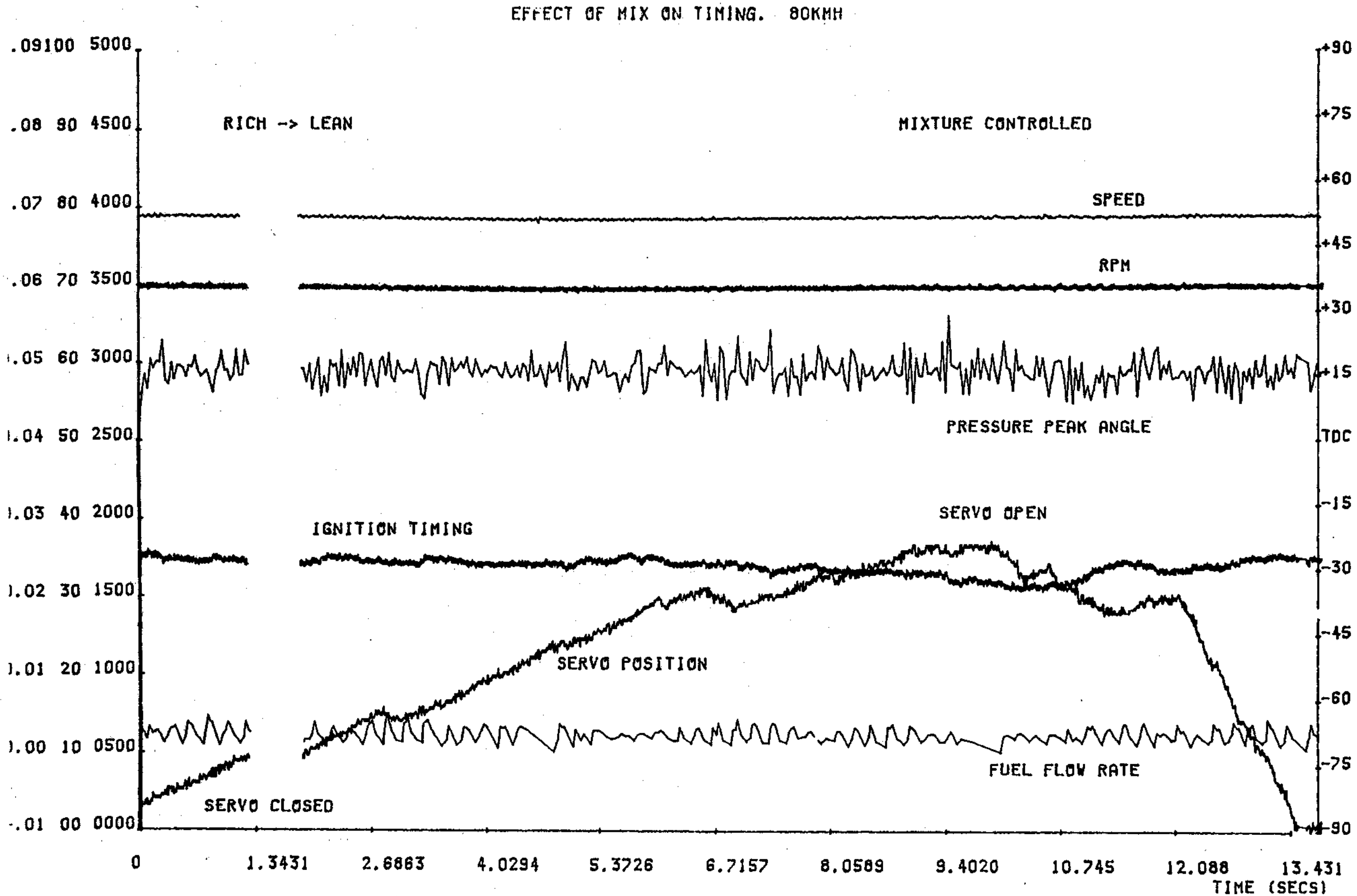


Fig. 19 - Timing and peak position response to servo opening

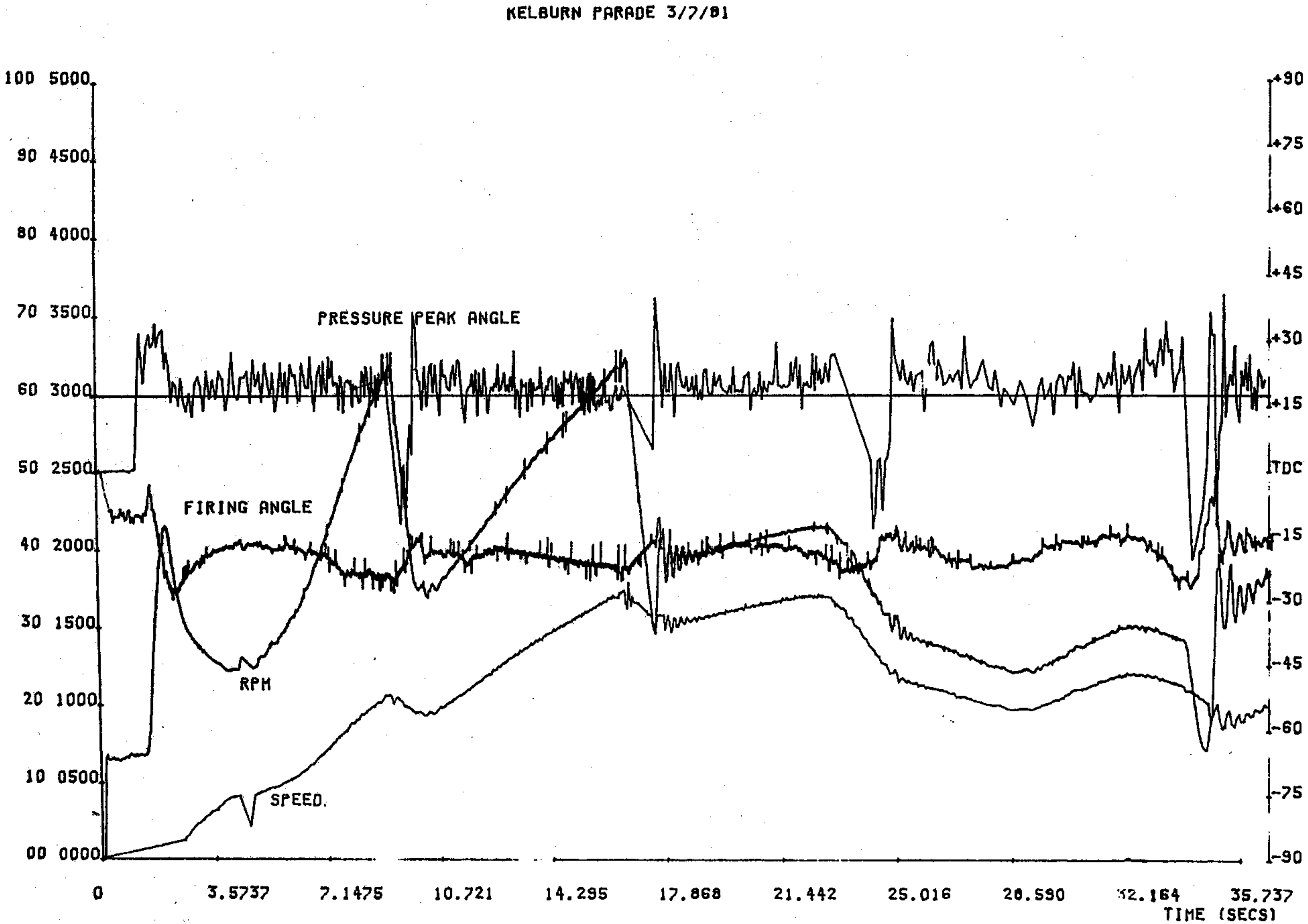


Fig. 20 - Rapid acceleration and gear changes:
(a) Original scale

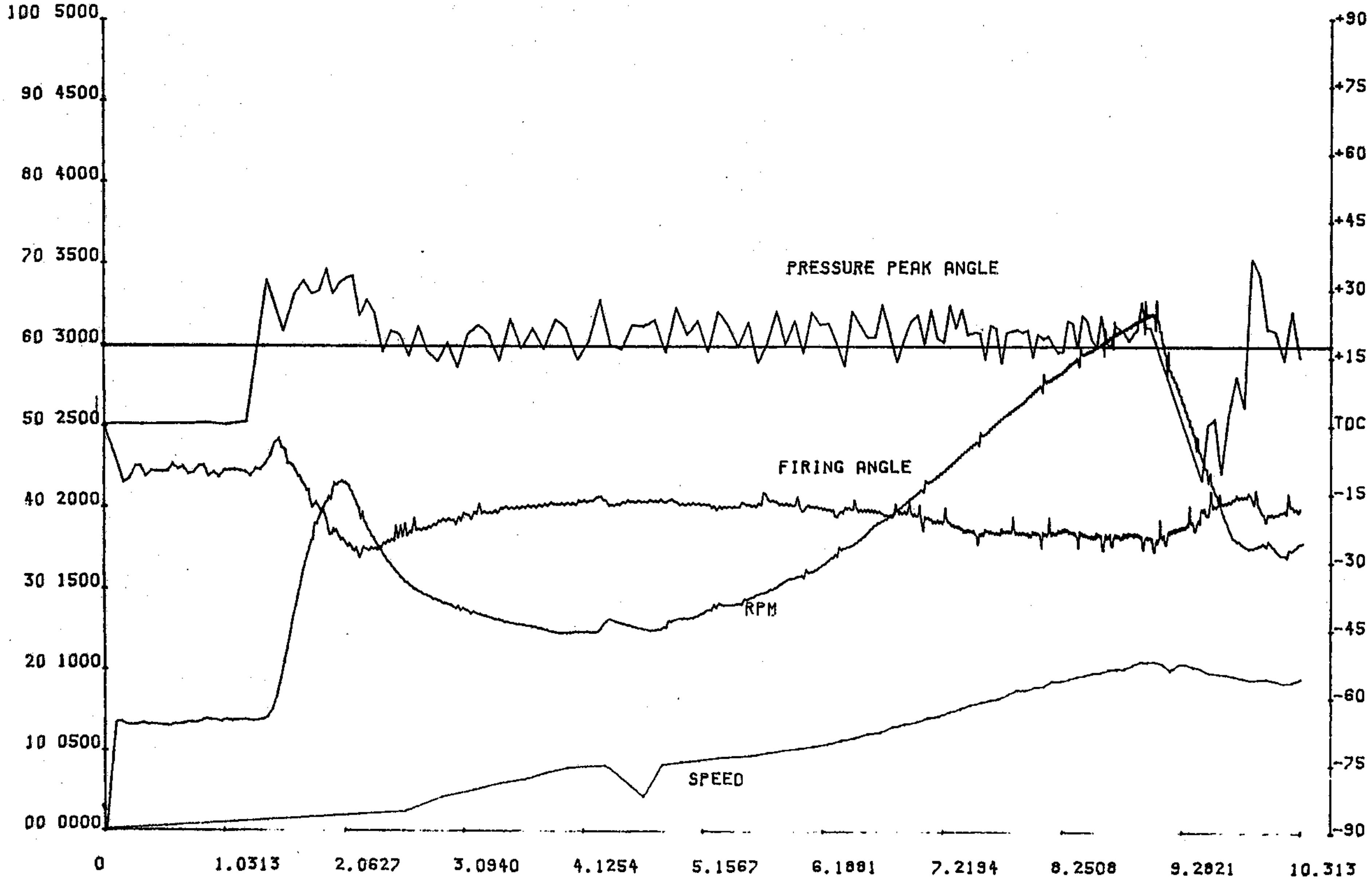


Fig. 20 - Rapid acceleration and gear changes:
(b) Expanded scale