PREDICTIVE CONTROL FOR A THROTTLE REGULATOR IN VEHICLE TESTING

by

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(ABSTRACT)

A method of predictive control is used in the regulation of a vehicles' speed in an environmental test cell with a wind tunnel. The vehicle speed is regulated through the throttle while the vehicle torque is controlled with a dynamometer. The predicted throttle position for the requested speed is based on torque, speed, and throttle position curves. The predictive control works in conjunction with an integrating speed regulator. The predictive control sets the throttle position when the speed error is above a set limit. Otherwise, the integrating regulator controls the speed.

A description of both the dynamometer and throttle control hardware is included in the thesis. The throttle control software is described in detail since most of the regulating functions are digital.

Both simulation and on site tests are described. Test results are provided by strip chart recordings.

ACKNOWLEDGMENTS

Just a few short words to thank all the people who helped and encouraged me in completing this project. If it were not for the help and support I received, this thesis would never have been done.

First, and most important, I would like to thank my wife, Mary Sue, for her help in editing, proof reading, and her endless encouragement. Of even more help was Mary Sue's patience for putting up with my late nights at work and home while working on this thesis.

At General Electric, I would like to thank John Carlton for his help and cooperation. John Carlton designed the hardware and software for the dynamometer and master control microcomputer.

Also of assistance was Roger Petty, General Electrics' application engineer. He helped me on many design and theoretical problems and questions. Of equal help was Richard Beerman, a senior control engineer.

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CONTENTS

CONTENTS

APPENDIXES

TABLES

FIGURES

FIGURES

FIGURES

CHAPTER 1

INTRODUCTION

Vehicle testing is considered a very important aspect to the health and profitability of the automotive industry. Not only have customers been demanding quality vehicles, but government regulations have been becoming more strict, while costs keep spiraling higher.

There are many types of tests that are performed on vehicles, and many methods for performing these tests. One such test is to run the vehicle as it will be used, under a variety of operating and environmental conditions. The purpose of the test is to determine how well the vehicle performs and whether the total vehicle and its subsystems maintain their specifications. Also, design flaws or problems can be discovered before production of a new vehicle gets too far down the road. In order to reduce the expense of running such tests and to ease the gathering of data, environmental test cells are used. The testing is performed inside a wind tunnel with the vehicle operating on a set of rollers controlled by a dynamometer. The vehicle and the surrounding environment are automatically controlled so as to simulate actual driving conditions found on the road.

1.1 The Project

One such test system has been built by Ford Motor Company in Dearborn, Michigan. General Electrics' Drive Systems Operation supplied the electrical control for the environmental test cell.

The basic structure for the test enclosure is a fifteen foot diameter wind tunnel, capable of producing winds up to 100 miles per hour. The vehicle is placed inside the wind tunnel on two sets of rollers, one for the rear wheels and one for the front. The test cell is capable of testing anything from small front wheel drive hatchbacks to large three axle diesel trucks. The wind tunnel is designed such that the temperature, humidity, and lighting can be accurately controlled.

The vehicle torque or speed can be controlled by two regulated dynamometers connected to the front and rear vehicle rollers. The vehicle torque or speed can also be controlled by a regulated throttle controller.

In testing a vehicle, the dynamometer and throttle controller cannot be regulating the same variable. The most common regulator configuration for testing vehicles is one in which the dynamometer controls the torque, and the throttle controller regulates the speed of the vehicle.

1.2 The Problem

One of the major goals in testing with this type of system is to determine how well the vehicle and its subsystems will hold up under actual driving and environmental conditions. The road and driving conditions are simulated by torque regulation of the vehicle, with the required torque being determined by a "Road Load" simulator program. This program essentially calculates the required torque based on road conditions and vehicle parameters.

In tests of this type, it is very important to obtain a high degree of accuracy and repeatability. For this reason, the torque is controlled by the dynamometer(s), which can be very fast, usually about ten radians per second.

The speed of the vehicle is controlled by the throttle regulator. Again, accuracy of the test requires the vehicle to respond to disturbances in torque or speed reference changes in a consistent manner, regardless of the operating conditions. Also, accurate steady state speed regulation is a necessary condition, which requires a fairly fast speed regulator. As with the torque regulator, the goal for the speed regulator is around ten radians per second.

The problem is that the vehicle characteristics change depending on the operating conditions, mainly the torque and speed. This is especially pertinent to regulating the vehicle speed through the throttle. With fixed tuning parameters for the speed regulator, the speed response characteristics will be different for various torque and speed levels. In some cases the response will be over damped, while with other conditions the response will be under damped. Of course, some points will demonstrate a critically damped response.

Another problem that can become evident is the interaction between the throttle speed regulator and the dynamometer torque regulator. If the two regulators are set close to the same speed, they will interact, causing the speed and torque of the vehicle to become unstable. This is because speed and torque are related variables within the vehicle, so that the two regulators are coupled.

The problem of inconsistent speed response is not solved as easily as the problem of interacting regulators. The use of variable tuning parameters is one possibility. But the amount of tune up time for a vehicle can be prohibitive. Even if vehicles of the same type are used, fine tuning is needed for each vehicle in order to obtain good consistent responses at all operating points.

1.3 The Solution

The solution to the problem is to use a predictive control scheme along with a digital throttle speed regulator. Figure 1.1 illustrates a simple block diagram of the regulating scheme used to control the speed and the torque of the vehicle.

The diagram shows the torque of the vehicle being regulated by the dynamometers through the vehicle rollers, while the speed is regulated through the throttle by either the digital closed loop regulator or the predictive control.

Under steady state conditions, the vehicle speed is controlled by a single integrating closed loop speed regulator. A disturbance in the system, or a change in the speed reference will cause the speed error to increase. When a preset limit is reached, the speed regulator will be switched off, and the system will immediately set the throttle to the position required to obtain the speed called for by the reference. The required throttle position is based on stored torque, speed, and throttle position curves for the vehicle. Once the speed error is back within another set of predefined limits, the closed loop speed regulator is enabled again and the vehicle speed will be regulated with little or no error.

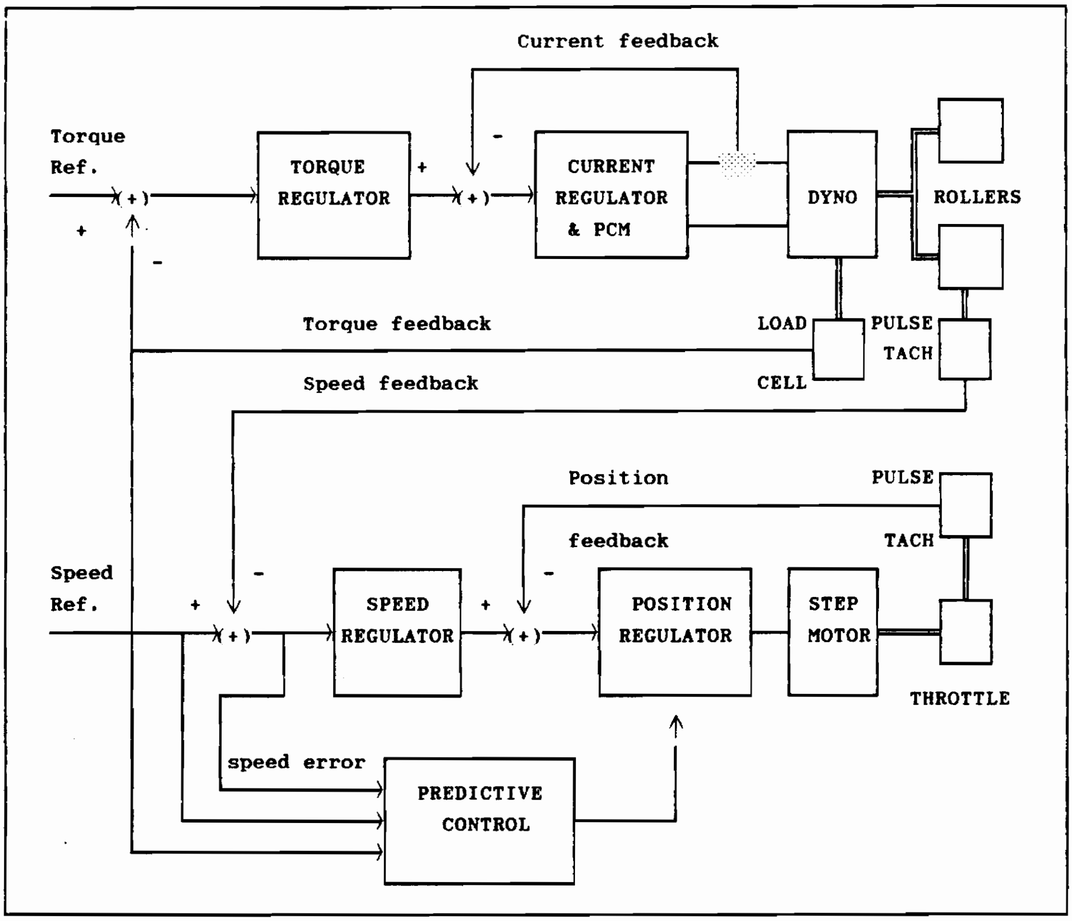

FIGURE 1.1

OVERALL SYSTEM DIAGRAM

This configuration results in a more consistent response to torque disturbances or changes in speed reference. The response time of the speed regulator can be increased without causing regulator interaction. The regulator interaction is reduced with the predictive control because there is less throttle action when the speed regulator takes over. This reduces the torque disturbances when a change in speed is requested.

1.4 The Task

The previous material is a short introduction to the Ford vehicle test system, the problems associated with the regulators, and the potential solution to the problems. This section includes a short description of the tasks required to implement the control system and the author's contribution to the development and design of the Ford project.

The author was presented with the opportunity to work on the Ford environmental test cell project as an excellent subject for a Masters' thesis. The primary task was to develop and design the throttle regulating system with the ability to effectively regulate vehicle speed with a consistent response over all operating conditions, while maintaining good steady state accuracy. The predictive control as described in section 1.3 is the result of author's work in the design of the throttle controller.

The responsibilities in regard to the Ford project included more than just the throttle regulators. The work required included designing the hardware and software for the throttle control, and performing a system test in cooperation with the other engineers on the project. It was also necessary to design a hardware and software interface for the throttle actuater.

Additional functions developed and implemented by the author are listed below. Some of these functions are described in detail in Chapter three.

1. Throttle speed regulator.
2. Throttle torque regulator.
3. Predictive control for the speed regulator.
4. Mode selection and control.
5. Bumpless switching of regulator modes.
6. Upload and download of the engine map data to and from the MicroVax computer.
7. Upload and download of vehicle and regulating parameters to and from the MicroVax computer.
8. Data set selection from five sets stored in the microprocessor memory.
9. Setting of full and idle throttle positions for calibration.
10. Braking function implemented through the master control and dynamometer.
11. Initialization of the indexer (Compumotor's stepping motor controller).
12. Control software for the indexer.

Three other engineers at General Electric had responsibility for the rest of the system. This included the fan drive for the wind tunnel, the dynamometer controller, the master control microprocessor, and the operator station devices. The MicroVax hardware and software was supplied by DSMA, a Canadian company which specializes in data collection and automatic control of vehicle test cells.

A high degree of coordination was required between the author, the engineer in charge of the master control, and DSMA since the different subsystems have a high degree of interaction.

This concludes the introduction to this paper. The next chapter is a literature review describing what has been published in regards to engine and vehicle test systems, with the emphasis on the throttle controller. Chapter three describes in detail the hardware and software required for the test cell control system. The dynamometer and master control subsystems are included in this chapter for completeness, but the emphasis is on the work performed in regards to the throttle controller and the predictive control. Chapter four discusses the testing performed on site and the testing with the use of software simulation code. Chapter five is a discussion of the results of testing along with possible changes and improvements, and finally a summary of the project.

CHAPTER 2

LITERATURE REVIEW

An extensive search of the literature from the late 1970's through 1988 revealed no papers or articles dealing specifically with throttle control systems for vehicle or engine test systems. All papers and articles found addressed the vehicle or engine test system with the throttle control only as a part of the system. In all cases, the emphasis was on the dynamometer system and/or data collection methods and techniques. Most of the papers dealt with engine test systems as opposed to chassis dynamometers. All of the papers researched included systems which had computer or microprocessor control, some of which where quite complex* [6].

Some of the papers reviewed did not have any material on throttle controllers, but included other items of interest with respect to vehicle and engine test systems. For instance, Morgan et al. [9] described a vehicle environmental test chamber with a large fan for simulating vehicle windage. This test facility was used to evaluate the performance of lubricants and fuels over a wide range of operating conditions. The dynamometer used was a full DC machine with a unique load

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*Numbers in brackets designate references in the bibliography at the end of this paper.

measuring system which allowed measuring the vehicle tractive effort at the wheels. Full road load simulation was used to simulate actual vehicle operation. The dynamometer controlled the speed of the vehicle, but the speed reference was based on desired and actual load feedback. This mode allowed for better and more simple control of the dynamometer and allowed for zero speed control.

Another paper by D'Angelo and Gafford [10] included some useful information on the derivation of road load equations and methods and techniques for simulating inertia for vehicle testing.

Sobolak's paper [11] included some information on modeling a vehicles' combustion engine along with its drive train and gearing. This information could be useful for analyzing a vehicle test control system.

A number of the articles and papers researched had some type of throttle control involved in the testing of diesel engines. A paper by Raine and Salisbury [8] described a test system which used an eddy current disc dynamometer with a throttle controller which regulated the engine speed while the dynamometer regulated the engine torque. The system could be controlled manually or by computer.

Marzouk and Watson [7] described a test system which used a stepping motor for throttle control. The stepping motor had a speed of 4000 steps per second with a resolution of 2000 steps per revolution. The paper did not include details on the regulation methods used with the throttle control.

Poiasek et al. [6] described a complex ten cell engine dynamometer test facility. The throttle control actuater was not described, although the throttle was computer controlled, regulating either engine speed, torque or throttle position. Under manual control, only throttle position regulation was available. Speed feedback was derived from the engine distributor, and throttle position feedback was from either linear or rotary transducers. Calibration of throttle position was by percent of full travel or absolute position. DC machines were used for the dynamometers with SCR control. Each test cell was tied to a satellite computer, which could have full control of each cell. Data collection was quite extensive, with data rates variable up to ten samples per second, and bursts as high as 30,000 samples per second for short intervals. Extensive automatic calibration of all I/O is conducted before each test in order to maintain consistency and accuracy across all test cells.

An interesting system that controls the throttle, brake, and gear shifting (manual transmission) of a vehicle was described by Willn et al. [4]. Vehicle loading was performed on a roller dynamometer. The throttle was controlled by an electrohydraulic actuater with linear position feedback. The system included computer control with an extensive procedure to "teach" the system the proper positions for each actuater for each vehicle tested. Speed feedback for the throttle control was from the rollers when in a test cycle, but switched to engine speed feedback during a gear change. The method of speed regulation was not covered in this paper.

Another system which used a stepping motor for the throttle controller was described by Watson et al. [3]. The throttle controlled the speed of the vehicle through a microprocessor based proportional regulator, with feed-forward compensation for anticipated load change demand. An algorithm for the speed regulator was presented, but it was not explained in much detail. A settling delay time of .5 seconds was imposed between the position commands to the throttle stepping motor in order to reduce engine speed overshoot. A tolerance of ten RPM was the goal for steady state speed regulation. Maximum stepping motor speed was 1.18 seconds from minimum to maximum throttle position. The main emphasis in this paper was with data collection since the test facility was for engine transient testing. The system included data sampling rates as high as 500 Kilohertz.

Germane and Heaton [2] described a dynamic test facility which used an electro-pneumatic system for the throttle controller, and an inductor type dynamometer with a hydraulic motor, which allowed for motoring from the test engine. The paper described a modified proportional-integral difference equation used for the throttle control, along with the methods used for tuning the regulator. The proportional and integral gain constants for the regulator were variable and dependent on the rate of change of the speed reference and the actual engine speed. The relationships for gains to rate of change of speed reference and actual engine speed were experimentally derived. The paper described a feed-forward system in which the throttle gains were updated four seconds prior to a ramp input. This was necessary in order to compensate for the lags inherent in the engine response.

Germane and Heaton made reference to a paper [12] which described a combustion engine as being a first order system with a time delay, which is proportional to the inverse of engine speed. However, Germane and Heaton found that "The system appeared to be of first order with a time delay, but a functional relationship of the delay in terms of the dynamometer setting and the throttle actuater signals could not be determined" [2].

The throttle was controlled from a microprocessor based controller, with references and command signals from a computer, which also controlled the dynamometer and data collection. The micro based throttle controller had a cycle time of .5 seconds.

A throttle controller which used a system similar to the predictive control was described in a paper by Koustas and Watson [1]. The system described is located at a research facility at the Imperial College in England. The engine test bed used eddy current dynamometers and stepping motors for the throttle control. A Texas Instrument TMS 9900 sixteen bit microcomputer was used for the throttle controller and load control. Again, the main emphasis of this paper was on the system as a whole, so some details on the throttle control were quite limited.

A stepping motor for the throttle actuation was used because they are relatively easy to interface with computer control and they feature automatic holding torque for steady position conditions. However, because of the limited speed-torque characteristics of the stepping motors used, "a memory table provides the optimal acceleration-deceleration rates for the particular stepper used and the load that it drives" [1]. The constants used in the memory table were derived experimentally when the engine was first installed. The paper goes into considerable detail on the derivation of the optimal trajectory of the stepping motor control.

The system had five control modes, two of which used an engine throttle/torque/speed map with the throttle controller. For this mode of operation, a "software closed-loop PID is used for engine speed control with the set point band modification when close to the target [5]. Torque feedback is incorporated in the offset of the positional form of the PID controller (fig. 3). This allows the engine map to be directly related to actuater position and compute a feed forward correction for the effect of torque on speed. The engine map is stored as a 3D table of speed, torque and actuater position with the smoothest gradient interpolation performed online" [1]. This is the only information offered in regards to this mode of the throttle control.

Dynamometer systems supplied by General Electric's Drive System Operation in Salem, Virginia have used a variety of throttle control systems. Some of the systems used a Daytronics hardware controller which regulated the throttle for speed, torque, or position. This system was not computer controlled and required fine tuning when different engines or vehicles were to be tested. Another system used a microprocessor controller which regulated vehicle speed or torque through the throttle. The throttle actuater was a small

DC motor controlled by a hardware position controller, driven by the microprocessor.

In summary, there is a lot of published material on dynamometer and test cell facilities, but very little that relates directly to engine or vehicle throttle controls. The majority of systems are computer controlled, with various types of regulating schemes. The most popular throttle actuater seems to be the stepping motor due to the ease of interfacing with a computer or microprocessor. Most of the papers reviewed emphasized the dynamometer system and data collection, with test results emphasizing these systems.

CHAPTER 3

MATERIALS AND METHODS

This chapter describes both the hardware and the software used to implement the control system for the vehicle test cell, with an emphasis on the throttle control processor and the predictive control. A description of the software language is included since it is very pertinent to how the predictive control is implemented.

The throttle speed regulator with predictive control can be divided into two major systems. The first is the hardware, which can be described as the "materials" used to implement the control functions. Included within the "materials" section is the software language used to implement the control functions in the processor. The second system is the control software for the processor, which implements the "method" of control.

The throttle control cannot be considered in isolation, so short descriptions of the other hardware and control functions are included for a better understanding of the system. Thus, for the whole control system, the hardware can be divided into seven major groups.

1. Digital processors.
2. Operator control stations.
3. Analog torque regulators for the dynamometers.
4 DC power converters.
5. Dynamometers.
6. The throttle actuater.
7. Feedback devices.

The software is divided on a functional basis, and will be limited to the following areas:

1. Dynamometer torque regulation and road load simulation.
2. Throttle control software organization.
3. Throttle speed regulator and position control.
4. Predictive control and related support functions.

The next section, 3.1, describes the hardware system, while section 3.2 discusses the software languages used. Finally, section 3.3 describes the regulator and software functions, including the predictive control.

3.1 The Hardware System

Figure 3.1 shows the complete hardware system with the major lines of communications. The three digital processors are shown on the left. The first is a Digital Equipment Corporation MicroVax minicomputer. The master control and throttle controller are General Electrics' Distributed Micro Controllers (DMC), which are Intel 8086 based micro computers. The three processors communicate via the Control Signal Freeway (CSF), a high speed data link which uses global memory and token passing.

The portion of the system that the author was responsible for designing included the throttle control DMC, the position control hardware, stepping motor, and the position feedback pulse tachometer. The design included the necessary interface with the CSF, the operator station, and speed and torque feedback. The other subsystems are described next for completeness. This section ends with a detailed description of the design for the throttle controller.

The MicroVax is used primarily for data collection and automatic control of the testing. The MicroVax has a number of testing plans stored on disk, which the operator selects via a terminal. A test plan consists of a speed and torque profile for the operation of the

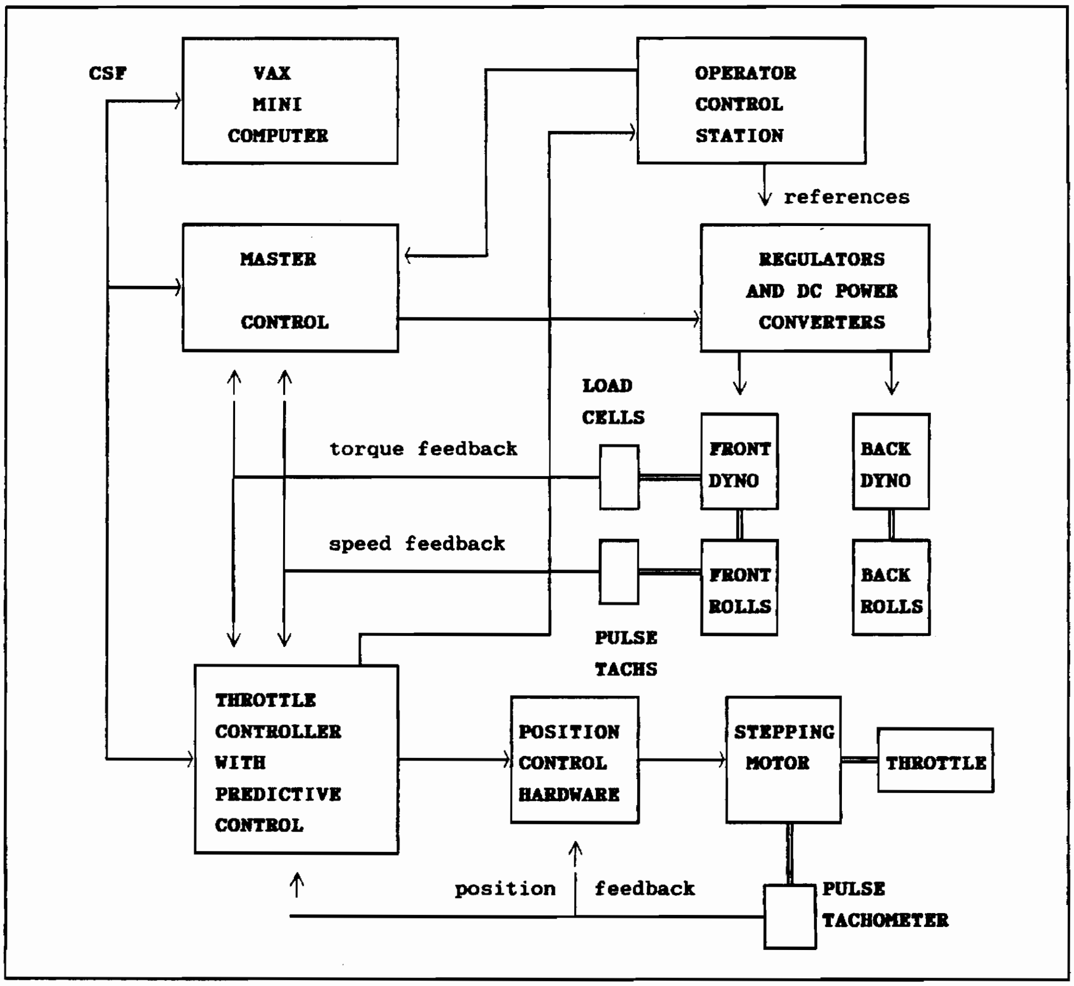


FIGURE 3.1

HARDWARE CONTROL DIAGRAM

vehicle, and includes the environmental conditions. In conjunction with the test plan, the MicroVax also stores the vehicle parameters necessary for the road load simulator and regulator tuning parameters for the throttle controller. Once a test is initiated, the MicroVax selects the correct regulating mode for the dynamometers and the throttle controller, downloads the required road load and regulator parameters, turns all systems on, and then sends speed and torque references according to the test profile. While the MicroVax is controlling the operation of the vehicle and the environmental conditions, it collects all relevant data and stores it in a data base, which is then used for the presentation of the test results.

The operator control station is used for manual control of the system and also displays a selected number of operating parameters during either automatic or manual tests. The whole system is totally independent of the MicroVax when manual mode is selected. As can be seen in Figure 3.1, references for the dynamometers and the throttle controller are sent directly to the appropriate system in the form of analog signals. Feedback for torque, speed, and throttle position are also sent directly to the operator station as analog signals. Control signals from the operator station are communicated via an RS232 serial link with the master control DMC. Included as part of the operator station is a CRT system with a keyboard for control and data input. The CRT system is used for the display of a number of screens which allows for calibration of the system and data input that pertains to the vehicle being tested. The CRT system is menu driven for ease of operation in manual mode. Due to the high degree of interaction necessary for the throttle controller, the author designed three of the screens for the CRT system. These included: a screen to instruct the operator through the required actions to perform the engine map procedure (described in section 3.3.4.1), a screen for vehicle and regulator parameter data entry for the throttle controller, and a screen for initiating such functions as upload and download of data, selecting data sets, setting the full and idle throttle position, and initializing the indexer.

The master control is actually made up of two DMC's (Distributed Micro Controllers) mounted in the same electronics module. The first DMC is a high speed processor (20 milliseconds) used to derive the vehicle acceleration rates from the speed feedback pulse tachometers. The acceleration rates are used to compensate for inertia in the dynamometer and simulated inertia in the vehicle. The inertia compensation is part of the road load simulator, where acceleration torque requirements are calculated. Acceleration rates must be derived in a high speed processor in order to reduce the lag time constant inherent in a digital processor. This is very important because inertia compensation can have a large impact on the torque reference. The second DMC of the master control provides a variety of control functions. It is used for the main interface between the MicroVax and the operator station. It controls the mode and reference selection for both the dynamometers and throttle controller, and performs the actual calculations required for the road load simulator. The master control DMC directly controls the dynamometer DC power converters through a serial data link, and supplies references to the dynamometer torque or speed regulator in the form of analog signals through D/A converters. Communications between the high speed processor and the master control DMC is over an extended parallel bus on the backplane of the master control electronics module.

The DC power converters essentially rectify three phase AC voltage to a variable DC voltage for the dynamometers by firing six SCR's in the proper sequence and with the correct phase angle. The phase angle determines the level of armature DC volts, and is controlled by the analog torque or speed regulator. These regulators essentially drive the dynamometer's DC voltage, through the power converter, to the required level that is necessary to obtain the specified dynamometer torque or vehicle speed. More details on the dynamometer torque regulator will be included in section 3.3.1.

The throttle controller with predictive control, shown on the lower left in figure 3.1, is the third digital processor in the system, a Distributed Micro Controller or DMC. Figure 3.2 shows a detailed diagram of the throttle controller DMC and the throttle actuater hardware. The DMC communicates with the outside world through the analog IO, discrete IO, and the Control Signal Freeway. Torque feedback is from the

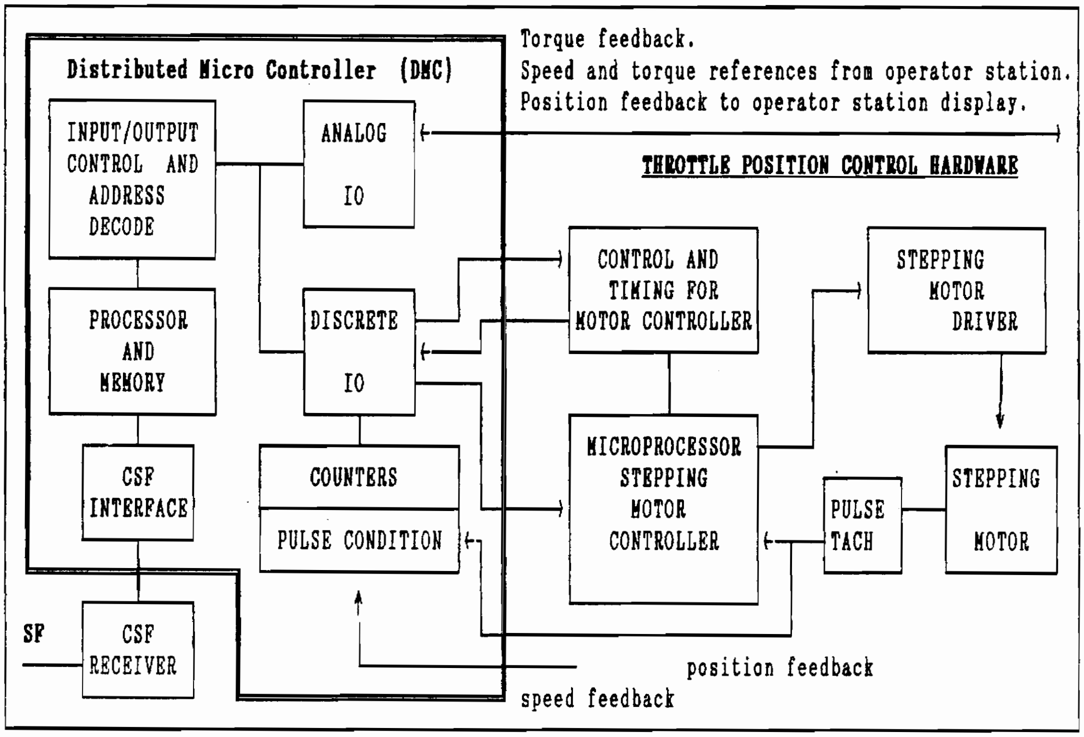


FIGURE 3.2

THROTTLE CONTROLLER HARDWARE

dynamometer load cells, and manual references from the operator station are brought into the DMC through analog to digital converters. The pulses from the speed and position tachometers are first conditioned and then sent to up/down counters, which essentially count the number of pulses from the tachometers. The counters are tied directly to the DMC IO bus so that the value in each counter can be accessed by the processor through the discrete IO.

The vehicle throttle is controlled by a Compumotor P106-308 microstepping motor and motor driver. A stepping motor is used in order to obtain a relatively high torque (5,000 ounce-inch) with a small sized motor. The high torque is required in order to move the throttle of large trucks. The motor driver is controlled by a microprocessor based indexer, also supplied by Compumotor. The indexer moves the motor by issuing a pulse train to the driver, with each pulse telling the motor to move by one step (scaling with the pulse tachometer was set at 4000 pulses per revolution). The velocity profile for the indexer, for moves of 90 degrees or less, would be triangular in shape. The closed loop position regulator in the indexer is not activated until the target position is reached. Thus, the pulse tachometer is used by the indexer more as a position maintenance function than an actual regulator.

There were several important considerations that had to be taken into account in designing the hardware for the throttle controller. One consideration was the memory capacity of the Distributed Micro Controller. The upper limit on memory for the DMC (without major modifications) is about 42 kilobytes for data and application code. This placed a limit on the number of data sets which could be stored in the DMC local memory. Each data set included the engine map throttle, position, and torque curves (121 real numbers), the regulator parameters, and the vehicle parameters. It was necessary to estimate the quantity of memory that would be used for the application code, and from there, it was determined that five data sets could be included in the local DMC memory.

Scan time was another important consideration. The use of a ten megahertz 8086 Intel processor with an 8087 math coprocessor helped keep the regulator scan time to a rate of 50 milliseconds. It was also necessary to design efficient software in order to keep the scan time to a minimum.

Designing the hardware interface for the Compumotor indexer was especially challenging. The indexer presented a problem in the way its command structure was organized. In order to cause the motor to turn to a specified position, it was necessary to first load four registers in the indexer through a sixteen bit BCD data bus, one at a time, with the required position data. Next, using the same data lines, the command to make an absolute move is sent. Also, the command lines to the indexer had to be strobed after the data had settled. Actually, only one register was required since the motor would never turn more than ninety degrees. With the above indexer command structure, the DMC would have had to go through four cycles in order to give just one position command, which was an unacceptable delay for a speed or torque regulator.

To solve this problem, the author designed a hardwired digital circuit which issued the appropriate commands to the indexer, in the proper sequence, and multiplexed the data lines from two sets of digital IO in the DMC. The design incorporated standard "AND", "OR", "LATCH", and "INVERTER" logic elements. The hardwired timing for the interface was accomplished using five Intel 8253 timers, which are software programmable directly from the DMC application code. Three of the timers are used as oneshots (set for one millisecond) while the other two are time delays (set for ten milliseconds). The delays are used to make sure the indexer receives the position data first, then the command data. A simple method was devised for multiplexing the position and command data using two sets of sixteen bit digital output cards. During the I/O cycle of the application code, the position data is written to the first set of sixteen bit outputs, while the command data is written to the second set of sixteen bit outputs. The sixteen bit I/O cards have the ability to output data either from the DMC or pass data via inputs on the card. The output mode is switched by pulling a control line to ground. The output of the second sixteen bit card is tied to the direct data inputs of the first card. The indexer is tied to the first set of outputs all the time. During the first part of the sequence, the indexer reads the position data after its data strobe goes high, then low (from one of the Intel 8253 timers set as a one shot). A time delay later, the mode of the first output card is switched so that its output is now the command data. The strobe to the indexer for reading the command data is then activated, at which point the indexer causes the stepping motor to move to the indicated position.

This hardware is indicated in Figure 3.2 as the "Control and timing for the motor controller". With this control, the four actions required by the indexer for a position move command are accomplished within one cycle time of the DMC.

3.2 THE SOFTWARE LANGUAGE

Of the three digital processors used to control the vehicle test system, the Micro Vax is programmed in Fortran, while the master control DMC and the throttle control DMC are programmed using General Electrics' Control Block Language, or CBL. A short description of the Control Block Language and its structure follows.

The Control Block Language essentially lets the programmer build analog circuits in the digital world. Blocks of simple functions are put together in the appropriate order to build a desired circuit or function. Figure 3.3 shows an example of some of the

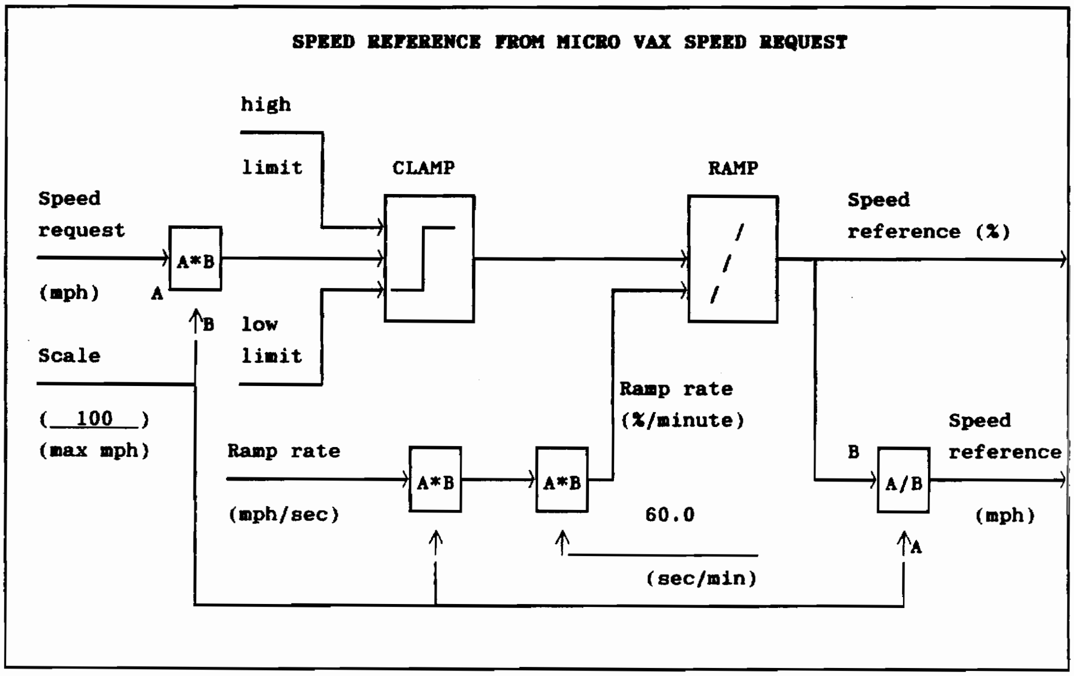


FIGURE 3.3

CBL EXAMPLE

blocks that are used and how they are tied together. The function portrayed is a simplified speed reference circuit for the throttle controller.

The CBL blocks used in this example are the multiply block, the divide block, the clamp block and the ramp block. Each block is actually a function which is written in assembly language and treated as a subroutine within the application code. The input and output parameters for the block are passed to or from memory via the processor stack. All of the circuits and functions that are built from the control blocks are considered the application code for the processor.

The parameters that are used to pass signals from block to block are assigned a mnemonic of up to twelve characters and related to the signal type in a "variable definition" file. Some of the signal types that can be assigned are: variable real parameters, constant real parameters, variable count parameters, and logicals. For constants, the value of the signal is assigned in the variable definition file. Also, the input and output (IO) for the system (including Control Signal Freeway IO) is defined within the variable definition file, where the absolute address is assigned. Mnemonics for the IO can be used anywhere within the application code.

A factor that makes the Distributed Micro

Controller so versatile for real time applications is that the application code can be split into a number of separate segments. Each segment can be assigned a priority and its own cycle time. The higher priority segments can interrupt lower priority segments so that the required cycle time will be assured for the fast segments. In the case of the throttle control DMC, the regulator segment has a very high priority with a cycle time of 50 milliseconds. Other segments which do not need to run very fast have a lower priority, with a scan time on the order of 400 milliseconds. With proper matching of application code size and assignment of cycle times, all segments will in fact run at their proper cycle times with time left over. The left over time is called "idle time" and should be around ten to twenty percent of the total processor scan time.

The code for a Distributed Micro Controller is developed on a Vax computer. The major files that are used for developing the code are: the application source code for each segment, the variable definition file, the standardized Control Block object code, and a link instruction file. Once the development of the application code (and the variable definition file) is complete, the files are linked together which produces object code that can be downloaded to the DMC through a serial communications port. The Vax linker also produces a document file, which is a listing of the code in block format. The document file also cross references all signals by segment and block number, and shows the definition, signal type, and absolute address of the mnemonics associated with each block. Appendix A describes the documentation in more detail, while appendix B is an example of the documentation produced by the software tools.

3.3 The Software and Regulating Systems

As with the hardware, the software and regulating systems can be split into two systems: the dynamometer control and the throttle control. As stated in the hardware description, the dynamometer regulation is primarily analog in nature, while the throttle speed regulator and predictive control are performed with a digital processor.

The throttle speed regulator and predictive control are tightly coupled with the dynamometer torque control through the vehicle engine, with both systems affecting the speed and torque of the vehicle. Because of the tight coupling between the two systems, it can be helpful to understand the configurations for both the throttle speed regulator (with the predictive control) and the dynamometer torque regulator. With known transfer functions for the regulators and subsystems, it will be possible to understand any changes or refinements required to improve the throttle speed regulator and the predictive control.

Keeping the above facts in mind, this section is split into four subsections. The first section describes the dynamometer torque control and the road load equation in detail. The second section is an introduction to the throttle control DMC, covering the scope and organization of the software. The third section details the throttle speed regulator and position control, while the fourth section covers the predictive control and related support functions. The last three subsections describe the systems that the author designed and implemented. Again, the first section is included for completeness.

3.3.1 Dynamometer Torque Regulation

Figure 3.4 shows the relationships between the master control, the torque regulator, the dynamometer, and the engine of the vehicle. The dynamometer current, torque, and speed feedback signals are detailed in this figure.

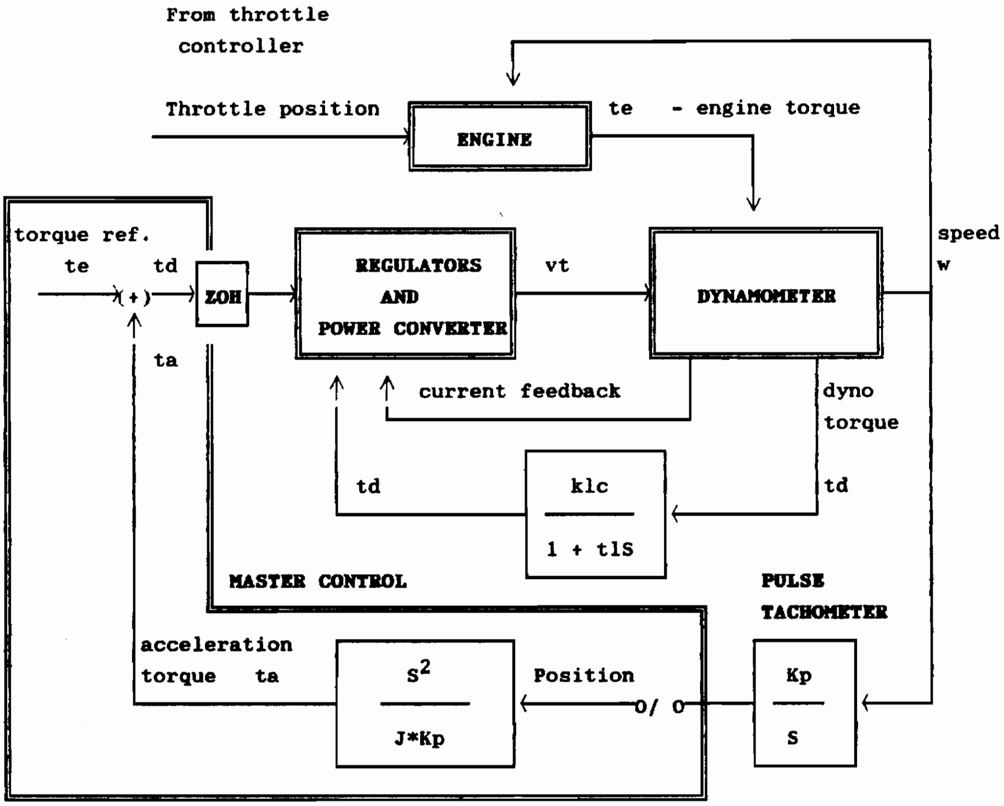


FIGURE 3.4

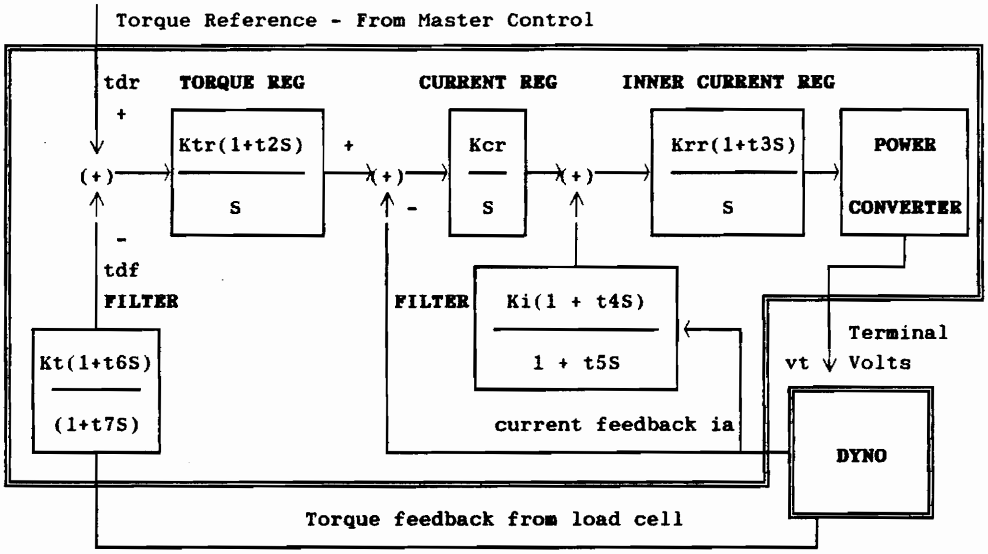
ENGINE TORQUE CONTROL VIA DYNAMOMETER

Torque feedback is from a load cell mounted on the dynamometer itself, with the feedback signal going directly to the analog torque regulator. The transfer function for the load cell and its associated electronics is approximated as a lag with a time constant of t1 and a gain of K1c. The load cell transforms the actual dynamometer torque to a voltage signal, with maximum torque equal to 8820 pound feet, giving a maximum output of five volts. Thus the gain is $5.7*10^{-4}$ volts/pd-ft. The lag time constant for the load cell is fairly high, around 400 radians per second.

Dynamometer current feedback is derived from a shunt in the armature circuit, with a gain of $2.5*10^{-4}$ volts/amp.

Speed feedback is used by the master control DMC in order to calculate the required inertia compensation for both the dynamometer and the vehicle. The pulse tachometer transfer function is an integrator, transforming vehicle speed (in RPM) to vehicle wheel position in degrees.

The transfer functions for the torque regulator are presented in figure 3.5 on the next page. The output of the inner loop current regulator determines the SCR firing phase angle for the thyrister power supply, which then produces the dynamometer terminal volts. The outer loop current regulator response is normally set around 30 radians per second, while the torque regulator response is on the order of ten radians per second. The



(See Figure 3.4 for load cell transfer function)

FIGURE 3.5

DYNAMOMETER TORQUE REGULATOR

high degree of filtering in the current regulator is required because most of the natural frequencies for the dynamometer and vehicle are within the range of the current regulator response speed.

Figure 3.6 shows the transfer function for the dynamometer, which is modeled as a standard DC motor. The dynamometer is controlled with a fixed field, so the transfer function includes only one mechanical lag time constant and one electrical lag time constant. The mechanical time constant in the model is determined by the inertia of the dynamometer through the vehicle drive train (J) and the friction within the system (B). In order to control the torque of the vehicle as opposed

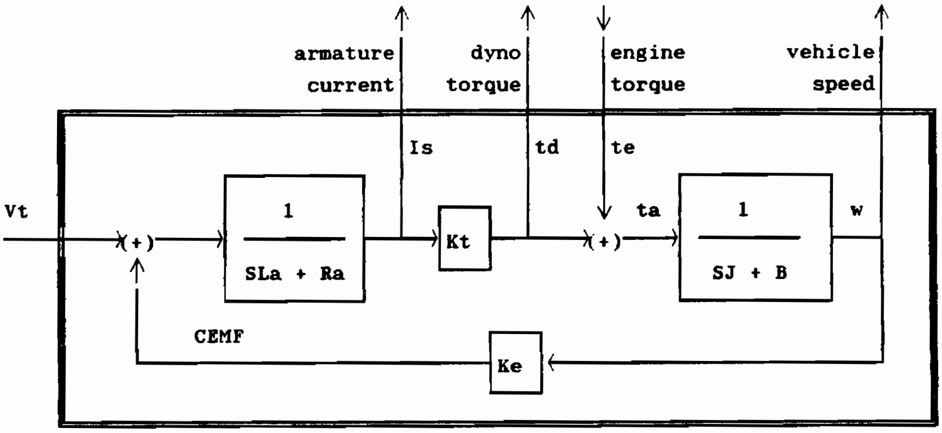


FIGURE 3.6

DYNAMOMETER MODEL

to the torque of the dynamometer, there must be compensation for the inertia and frictional losses within the dynamometer. This function is performed by the master control DMC.

The master control provides two functions in deriving the required dynamometer torque reference. The first is compensation for inertia and losses for the dynamometer. The second function involves the calculation of the required engine torque given the vehicle speed, acceleration, and environmental conditions. Figure 3.7 shows the basic components and required variables needed to perform these functions. Both speed and acceleration are derived in the master control high speed processor from the pulse tachometers mounted on the vehicle rolls. The road load equation is solved in the Master Control DMC software, with the final output

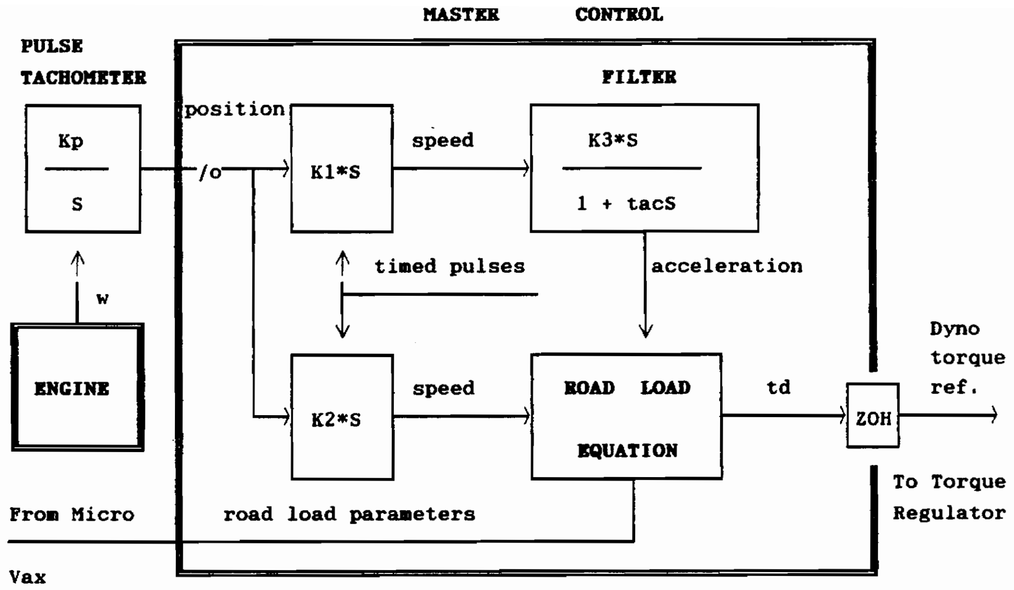


FIGURE 3.7

DYNAMOMETER TORQUE REFERENCE GENERATION

being the required dynamometer torque. The derivation of the dynamometer torque is covered in some detail because changes in the torque will have a large effect on the predictive control of the throttle regulator.

The required dynamometer torque reference is derived by relating the dynamometer torque to the torque produced by the engine of the vehicle. This relationship can be expressed as

$$Td + Tda + Tds + Tdf = Te \qquad (3.1)$$

Where:

Td = dynamometer torque as measured by the load cell

Tda = dynamometer and vehicle roll acceleration torque.

Tds = dynamometer and vehicle roll speed related torque losses.

Tdf = dynamometer and vehicle roll constant torque losses.

Te = torque produced by the engine.

The torque produced by the engine can be related to vehicle and environmental conditions, such that

$$Te = K0 + K1*V + K2*V^y + K3*(dV/dt). \qquad (3.2)$$

The factors K0 through K3 include all the necessary vehicle and environmental parameters required to define the engine torque. The definition of the factors are as follows:

$$K0 = (W*a1*G + W*R + A)*CRR \qquad (3.3)$$

$$K1 = W*B*CRR \qquad (3.4)$$

$$K2 = C*CRR \qquad (3.5)$$

$$K3 = a2*W*CRR \qquad (3.6)$$

The parameters used in equations (3.2) through (3.6) are defined below.

W = vehicle weight, in pounds (lbs).

a1 = Grade coefficient.

G = Surface grade, in percent, where 100% = 45 degrees.

R = Terrain rolling resistance, dimensionless.

A = Vehicle parasitic losses, in lbs.

CRR = Chassis (vehicle) roll radius, in feet.

B = Friction loss in the driven wheels, in lb/lb/MPH.

C = Vehicle windage, in lb/MPH^{y}.

a2 = Inertia coefficient constant, = .0455 Sec/MPH.

V = Vehicle speed, in MPH.

y = Vehicle windage exponent, normally set at 2.0, but varies with the vehicle.

The torque compensation (Tda+Tds+Tdf) in equation (3.1) can be expressed in the same manner as the engine torque, giving

FD = Kcr + (a2/CCR)*M*(dV/dt), (3.7)

where:

Kcr = Dynamometer and roll friction and windage, in lb-ft. (Tds + Tdf)

M = Dynamometer and vehicle roll inertia, in lb-ft^{2}.

The dynamometer and vehicle roll friction and windage torque losses are independent of the vehicle being tested, so the term Kcr is experimentally determined over the speed range of the dynamometer. With no vehicle on the rolls, the torque is measured at twenty different points over the speed range of the dynamometer. This data is stored in the master control DMC, and used with a linear interpolator to find the required torque loss for the dynamometer during the vehicle test.

Combining equations (3.2) and (3.7), the required dynamometer torque reference can now be expressed as

Td = K0 + K1*V + K2*Vy + K3*(dV/dt) - FD. (3.8)

Equation (3.8) is the road load equation which is solved in the master control DMC. Vehicle speed and acceleration are derived from the pulse tachometer feedback through the high speed processor. Note that the dynamometer torque reference (and thus the load cell feedback) can change via two methods. One is for the environmental conditions to change (road grade, road surface quality, etc.), while the other is a change in speed. For a change in speed, the change in torque is required for both the different speed, and the acceleration torque necessary to get to the new speed. This is especially important as it has a large impact on the predictive control of the throttle regulator. The prediction of the throttle position is based on the vehicle speed reference and the torque feedback. As the vehicle is accelerating, the throttle position will be at a higher setting (lower for deceleration) than is necessary for the final steady state speed. This higher throttle setting is necessary, as this is how the engine will produce the accelerating torque to obtain the higher speed.

This completes the descriptions of the dynamometer and the associated regulators and code. The rest of this chapter describes the software that the author developed and designed. This includes details of the throttle control DMC software organization, the throttle speed regulator, and the predictive control and required subsystems.

3.3.2 The Throttle Control Software Organization

Before moving on to the details of the throttle speed regulator and predictive control, a short description on the content and organization of the throttle DMC software is included.

The organization of the software can be very important for two reasons. First, well organized and efficient code allows for a higher scan rate for the regulators. Second, if the code is organized and written properly it can make the job of debugging and maintenance a lot easier. In organizing and designing the code for the throttle controller, the major goals where to minimize the amount of code in the regulator segment, organize the segments on a functional basis with a minimum of cross communications (between segments), and to keep the code as simple as possible for debugging and maintenance reasons. Even more important, the code had to perform all the functions required by the specifications.

The primary function of the throttle controller is to regulate the vehicle speed or torque via the throttle. In order to improve the regulation of the vehicle speed, the predictive control function is used to complement the standard speed regulator. In order to implement the predictive control the design required several support functions. The main support functions include the engine map procedure for easily collecting the engine characteristic data, the upload and download of this data to and from the MicroVax, and specialized mode control and switching.

A simplified diagram of the organization is shown in Figure 3.8. This figure shows the major functions (based on the segments) and the main interconnections between segments. What follows is a short description of each function, and how they interact with each other and with other parts of the system.

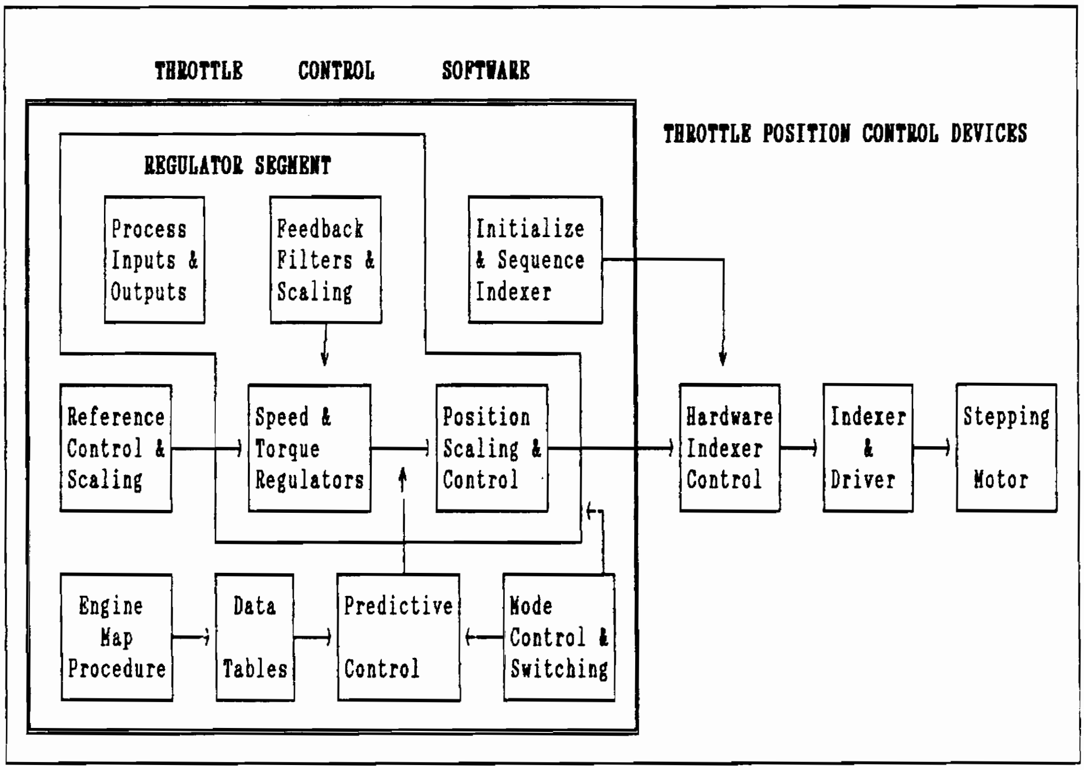


FIGURE 3.8

THROTTLE CONTROL SOFTWARE ORGANIZATION

The "Initialize and Sequence Indexer" block shown in figure 3.8 is actually two segments. The first segment initializes the indexer, which takes eight sequential steps. It is necessary to initialize the indexer after powering up the DMC or the indexer itself. The initialization segment sets such indexer parameters as velocity rates, acceleration rates, and selects the indexer for remote control of the remote power shutdown function (which removes torque from the motor). For each step of the initialization routine, the "Sequence Indexer" segment is called. This segment loads the indexer registers one at a time and then issues the command. Register and command data are preset by the initialization segment. The Indexer segment controls the actual indexer data and command registers and the indexer strobe lines through manual operation of the hardware control circuits.

The indexer segment also contains the code which actually turns the throttle on by canceling the "remote power shutdown". The initiation of the throttle on command is from the mode control segment, shown in the lower right of figure 3.8. (The ultimate origination of the throttle on command is from the operator at the operator station, or from the MicroVax. The signals are read into the DMC from the CSF, or Control Signal Freeway).

Another function which is available to the operator or the MicroVax is called "monitor mode". This is essentially the removal of stepping motor torque while the throttle is on. Monitor mode from speed or torque regulation is required in order for manual gear changes to take place. The mode control segment controls the logic for monitor mode; it first disables position commands from the regulator and then issues a command to the indexer segment to initiate a "remote power shutdown". The system is in monitor mode once the indexer segment has issued the last command to the indexer.

The regulator segment, by necessity, is the fastest segment in the throttle DMC, running at a 50 millisecond scan rate. The first function the regulator segment performs is to process all inputs - Control Signal Freeway data and commands, and feedback data. The last function it performs is to process all the outputs; the most important output being the position command to the indexer. The functions in-between, as shown in figure 3.8, are performed in the following order; First the feedbacks (speed and torque) are scaled and then filtered. The speed or torque regulation functions are next, and finally the position command scaling and control is processed. Only the speed regulator or the torque regulator can be active at any one time, although modes can be switched on the fly.

The regulators receive their references from the reference control segment. This segment essentially selects the manual or automatic reference per the mode control segment, then scales the reference from engineering units to percent. The segment also ramps the reference as specified by either the operator station or the MicroVax, and then limits the values to the maximum or minimum amount allowed. The reference segment contains the code for the speed reference, the torque reference, and the position reference. The position reference bypasses the regulators - it is used directly by the position scaling and control section.

The remaining segments shown in figure 3.8 are the engine map segment and the predictive control segment. The engine map segment is used to collect the data for the speed-torque-position curves used by the predictive control. The engine characteristic curves produced by the engine map segment are stored in the data tables, for use by the predictive control segment. The engine map segment is described in detail in section 3.3.4.1. The predictive control segment is enabled when the vehicle speed error becomes too large. At this point, the segment uses the data tables, speed reference, and torque feedback to calculate the required position reference. During this time, the speed regulator is disabled, and the position control section receives its position command directly from the predictive control segment, as shown in figure 3.8. The predictive control segment is described in detail in section 3.3.4.2.

As stated previously, the above description includes only the major functions in the throttle control DMC. Some of the other functions developed and designed are listed below:

1. Upload and download of engine map data and parameters to or from the MicroVax.
2. Selection of one of the five data tables to be used by the throttle control code.
3. Setting the idle and full throttle position (used for determining the indexer absolute zero position and for position control scaling).
4. Braking function. If the vehicle is not decelerating fast enough (detected by monitoring the speed error) during throttle speed regulation, the throttle control DMC will issue a command to the master control to increase the torque proportional to the amount of error. The added torque will act as a brake for the vehicle, causing a faster deceleration rate. This function is enabled or disabled from the operator station.

The sections to follow cover the details of the throttle speed regulator and the predictive control.

3.3.3 The Throttle Speed Regulator

The primary purpose of the throttle control DMC is to regulate the speed of the vehicle via control of the accelerator pedal. This is accomplished by implementing a proportional and integral regulator which outputs a position command to the indexer, which then drives the stepping motor for the throttle itself. Figure 3.9 on the next page shows the transfer functions involved in controlling the speed of the vehicle. This section will deal primarily with the speed regulator and position control for the indexer. Section 3.3.4 will describe the predictive control for the throttle DMC.

As stated previously, the speed regulator is implemented digitally using the Control Block Language in the throttle control DMC. Referring to figure 3.9, the speed regulator is shown as an integrator with a lead network, plus an independent proportional gain. The integrator with a lead network is simply an integrator with a gain of K_i plus a proportional gain of $K_i * t_a$. The extra proportional control was included for added flexibility in tuning the speed regulator. The lead/lag networks for the speed and torque feedback are also implemented in the throttle control DMC. The lag network for the feedback acts as a filter and is usually set for 0.1 seconds. The feedback lead network

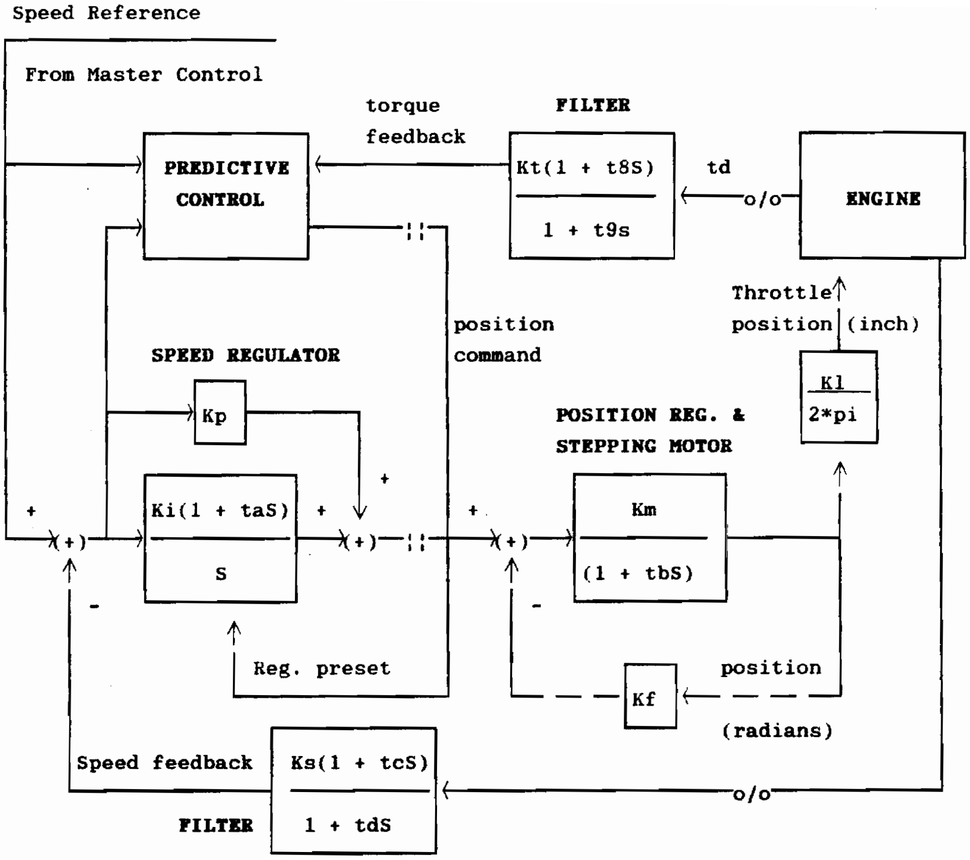


FIGURE 3.9

THROTTLE SPEED REGULATOR AND PREDICTIVE CONTROL

was used as a rate regulator (in combination with the integrator). The faster the feedback is changing, the more the feedback signal will "lead" the actual feedback. Tuning the lead time constant properly will reduce the amount of overshoot caused by the integrator.

The predictive control code, as shown in figure 3.8 in the previous section, resides in its own segment. A separate slower segment was used for the predictive control because it is not a regulator per se, so it does not need to run as fast. It also reduced the code in the regulator segment so that the actual speed or torque regulators can run faster.

The indexer (which performs the position control) and stepping motor are modeled as a lag between the position command and the actual position. The position feedback is shown with dashed lines because the indexer uses the feedback more for position maintenance than regulation. The lag time constant (t_b) is very small, about .01 seconds, and is based on strip chart recordings produced during the system test. In ramping the position reference at sixteen degrees per second, the strip chart recording shows a stair step function for both the reference and the feedback. The stair step function is due to the scan time of the DMC. The step size and time increment are the same for both the reference and the feedback, however the feedback lags the reference by 100 milliseconds. The lag is due to the time delays in the DMC, which has a scan time of 50 milliseconds. The lag time is accounted for by the time to read the position from the pulse tachometer plus the time to output the feedback to the strip chart recorder.

One factor which complicates the modeling of the indexer and stepping motor is the fact that the motor must be at a standstill before the indexer will accept and act on a new position command. This could result in a slightly choppy response for the throttle position. However, this should have a minimal effect on the system, since throttle position changes are relatively small, especially under steady state conditions. With small position changes, the motor will be able to reach its required position well within one scan time of the DMC, which is set for 50 milliseconds. Also, the throttle linkage and engine response will dampen this choppy response to a certain extent. As will be shown later, this limitation of the indexer is not important if step changes per scan are less than twenty degrees.

In addition to accounting for limitations in the indexer, it was necessary to design special software and hardware for the interface between the DMC and the indexer. The following paragraphs describe the design for the indexer position control.

The position control for the indexer is actually quite a bit more complex than indicated in figure 3.9. The output of the speed regulator (and the predictive control) is a real number scaled in percent of full throttle. This variable is then scaled to match what the indexer expects, which is a number between zero and 1000 (for zero to 90 degrees). The scaling is based on the previously set idle and full throttle positions. Next, the real variable is converted to BCD and stored in the output register for the indexer. As described in section 3.1, a special hardware circuit is used to accomplish four different steps for the indexer within one cycle time of the DMC. In order to initiate this cycle, the DMC must first reset five Intel 8253 timers, then change the state of a control output, which starts the cycle. The sequence of steps that the hardware circuit performs is detailed below:

Step 1: Load the indexer register with the new position data from its stored output points. Wait five milliseconds.

Step 2: Strobe the indexer command line to read position data. The strobe is one millisecond long.

Step 3: Load the indexer register with the command number to make an absolute position move. This is done by multiplexing another set of outputs onto the indexer register data lines. Wait five milliseconds.

Step 4: Strobe the indexer command line to read a command. The strobe is one millisecond long.

As soon as step four is completed, the indexer issues a train of pulses to the driver to move the stepping motor to the new position as dictated by the DMC.

The time between the DMC output cycle and when the indexer receives its command is about twelve milliseconds. This leaves 38 milliseconds for the motor to move to its new position. With step changes of less than twenty degrees, the movement of the motor takes place within one cycle time of the DMC.

As can be seen from the above description, the positioning control, indexer, and stepping motor do not limit the response time for the speed regulator as much as the scan time of the DMC does. The throttle DMC can run as fast as 30 milliseconds, or 33 hertz. If the DMC frequency were set at twenty times the bandwidth of the system, then the speed regulator could be as fast as ten radians per second. As stated before, the real limitation is due to the necessity of reducing the interaction between the throttle speed regulator and the dynamometer torque regulator and improving the consistency of the speed response. Thus the throttle speed regulator need not be much faster than five radians per second. The next section describes the design of the predictive control and how it interacts with the speed regulator.

3.3.4 Functions for the Predictive Control

The purpose of the predictive control is to improve the speed response of the vehicle to large changes or disturbances within the system. It should also provide a more consistent response across the speed and torque range of the vehicle under test. The predictive control code essentially "predicts" where the throttle needs to be in order to achieve the desired speed and torque for the test. The "predicted" position is derived from stored speed versus torque versus throttle position data for the vehicle under test. Under steady state conditions, the vehicle speed is controlled by the throttle speed regulator. If a change in speed reference or a change in torque causes the speed error to pass a specified limit, then the speed regulator is switched off, and the predictive control code sets the throttle to the position required by the speed reference and the torque feedback. Once the speed error is close to zero, the predictive control will switch off, and the speed regulator will switch back on. The integrator in the speed regulator is always preset with the actual throttle position so that the transfer from predictive control to speed regulator will take place without any bumps. The throttle controller will continue to use the speed regulator to control the throttle until the next disturbance takes place.

In developing the predictive control, it was necessary to produce two separate functions (each in its own segment). The first function is the method in which the data used by the control is collected and how it is organized. The data used in the control is called the "engine map", since it essentially maps out the characteristics of the vehicle engine. The second part is the predictive control function itself. The next section describes the organization of the engine map data, and how it is collected.

3.3.4.1 THE ENGINE MAP

Before work on the design of the engine map procedure could start, it was necessary to take a number of factors into consideration. The test cell has the capability of testing a full range of vehicles, all the way from small compacts to large semi trucks. For this reason, it was necessary to have the ability to upload and download engine map data to or from the MicroVax computer. In this way, when it is time to test a vehicle that has been used before, it will not be necessary to produce another engine map; the data is just downloaded from the MicroVax. Incorporated into the throttle controller was the capability of storing a total of five engine maps in the DMC memory. This is especially important when manual transmission vehicles are being tested, since each gear has its own engine map. If a different gear is required during a test, the operator must manually shift the gear and change the data set being used by the throttle DMC. In addition to the engine map data, regulator and vehicle parameters are also stored in five data sets. These parameters can also be uploaded or downloaded from the MicroVax. Another important feature that had to be determined was the resolution of the engine map. The three most important factors which had to be juggled in regards to this issue were the amount of memory available, the number of data sets that could be stored in the DMC, and the accuracy of the engine map. As stated previously, the maximum number of data sets turned out to be five due to memory limitations. The best resolution, a compromise between memory and accuracy, turned out to be eleven torque - position curves with eleven equal points for each curve.

In order to collect the engine map data for a new vehicle, a procedure is initiated either from the local operator station or from the MicroVax. The procedure runs the vehicle automatically through a long test in which the data is collected and stored in the throttle DMC. It is necessary for the dynamometer to regulate the vehicle speed, while the throttle control DMC sets the throttle position for this procedure. The vehicle torque is the independent variable. The throttle control DMC performs the sequencing, and thus controls the dynamometer speed reference through the master control DMC. The specific steps for this test are outlined below:

VEHICLE ENGINE MAP PROCEDURE

Step 1: Set the speed reference to minimum.

Step 1a: Set the throttle position to zero and wait twenty seconds for steady state (while checking for torque limits), then read and store the torque feedback.

```
    Step 1b: Set the throttle position to ten percent and wait twenty seconds, then read and store the torque feedback.
    Step 1c: Set the throttle position to twenty percent and wait twenty seconds, then read and store the torque feedback.
           :
           Repeat until throttle position is at 100 percent.
           :
Step 2:    Set the speed reference to ten percent speed.
           :
        Repeat setting throttle position from zero to 100 percent in ten percent increments.
        :
Step 3:    Set the speed reference to twenty percent speed.
           :
        Repeat setting throttle position from zero to 100 percent in ten percent increments.
    :
    Repeat until 100 percent speed is reached.
```

This procedure defines the resolution of the engine map; eleven torque data points are collected for each of the eleven throttle positions and vehicle speed points, for a total of 121 torque points. Table 3.1 on the next page shows the torque data which is stored along with the relationship to speed and throttle position.

A number of checks had to be incorporated into this procedure since the vehicle and dynamometer can be pushed to their limits. Torque feedback must be checked for both minimum and maximum limits at each step because some portions of the procedure cannot be obtained in a vehicle. There are two situations which can arise in this procedure. The first is asking the dynamometer to regulate to a speed without enough throttle for the engine to obtain that speed. The result would be negative torque. The dynamometer will "generate" current to force the wheels to turn at the required speed. When this condition is sensed, the step is aborted and the minimum torque is stored, and the next step is initiated. The second condition arises when the throttle is near maximum for low speeds. This is similar to applying the brakes on your car and stepping

TABLE 3.1

TORQUE DATA FROM ENGINE MAP PROCEDURE

Throttle Position	TORQUE (%) AT INDICATED SPEED (%)							
(%)	0% Speed	10% Speed	20% Speed	30% Speed	40% Speed	50% Speed	...	100% Speed
	Torque	Torque	Torque	Torque	Torque	Torque	...	Torque
00 %	T00	T01	T02	T03	T04	T05	...	T0A
10 %	T10	T11	T12	T13	T14	T15	...	T1A
20 %	T20	T21	T22	T23	T24	T25	...	T2A
30 %	T30	T31	T32	T33	T34	T35	...	T3A
40 %	T40	T41	T42	T43	T44	T45	...	T4A
50 %	T50	T51	T52	T53	T54	T55	...	T5A
:	:	:	:	:	:	:	.:.	:
100 %	TA0	TA1	TA2	TA3	TA4	TA5	...	TAA

down on the accelerator, which produces a lot of torque. The dynamometer will absorb the power produced at these lower speeds, but there is limit, and when it is reached the step is aborted and maximum torque is stored. For this condition, all the rest of the throttle settings are skipped (these throttle settings will always produce maximum torque) and the next speed reference is started.

In addition to checking for maximum and minimum torque, the engine map procedure also checks for steady state torque and speed feedback at each step. This is to assure that consistent and correct data are stored. If the speed and torque feedback do not reach steady state after a set time, then the engine map procedure is aborted. At this point, the operator needs to determine what is wrong, correct the problem, and start the procedure over again.

Once the procedure is finished, the operator will determine which data set out of the five to store the engine map in. The data sets are in constant memory locations which can be saved in EEPROM.

Now that the engine map data has been collected and stored, it can be used by the predictive control. The next section covers the details on how the data is used to "predict" the throttle position during a test.

3.3.4.2 The Predictive Control Function

In order for the throttle controller to perform the predictive control function, a three dimensional map of the engine characteristics is required. This map consists of the engine torque versus speed versus throttle position curves. The throttle position is "predicted" from the speed reference and the torque feedback. Before the code for this function could be developed, some basic decisions had to be made. The decisions involved the basic organization of the engine characteristic data and the methods in which the engine throttle position is found given the speed reference and vehicle torque. The following general description is the result of the author's development.

The engine characteristic data consists of eleven torque versus position curves, with each curve at a constant vehicle speed. The torque versus position curves start at a speed of zero percent, increase on ten percent increments, and end with a speed at 100 percent. The first action the code performs is to find the upper and lower speed points around the actual speed reference. Based on the upper and lower speed points, the relevant torque versus position curves are moved to the working tables. Linear interpolators are then used to find the throttle position from the upper and lower torque versus position curves. With two throttle positions known at the two fixed speed points, the required throttle position can be found from the known speed reference, again using linear interpolation. What follows is a more detailed description of how the predictive control function works.

The predictive control function is activated when the speed error becomes greater than a predefined limit. The first task the control performs is to determine the present incremental speed range of the vehicle - the upper and lower speed points around the actual speed. This is required in order for the system to select the correct subset of data tables for use in predicting where the throttle needs to be. The speed range is found by using ten CBL compare blocks. This block compares two real numbers and sets its logic output bit if the defined condition is true. In this case, the output is set if the speed reference is equal to or greater than a constant. The ten logical outputs that are set by this section of the code are shown on the next page. Logical operations are then performed on the above signals to determine the present incremental speed range of the reference. If SGT00 is true, but SGT10 is false, then the reference is between zero percent and 9.99 percent. The resulting signal is named S1&2, (named for "speed table one and two"). If SGT10

TABLE 3.2

SPEED RANGE SELECTION

Signal Name	Description
SGT00	Speed Reference is >= to zero.
SGT10	Speed Reference is >= to 10%
SGT20	Speed Reference is >= to 20%
SGT30	Speed Reference is >= to 30%
:	: :
SGT90	Speed Reference is >= to 90%

is true, but SGT20 is false, then the reference is between ten percent and 19.99 percent. The resulting signal is named S2&3, (named for "speed table two and three"). This logic is continued all the way to SGT90. If SGT90 is true then the reference is between 90 percent and 100 percent. The resulting signal is named S10&11, for speed table ten and eleven. As mentioned earlier, these logic signals are used to select the proper set of torque versus position curves.

When the engine map procedure is performed, the torque and throttle position data are stored in two contiguous tables in memory. One table is for the torque data, and the other table is for throttle position data. Each table is split into eleven subsets, with each subset corresponding to an incremental speed point. The first subset starts with a vehicle speed of zero percent, with the next for a speed of ten percent, then twenty percent and so on until 100 percent vehicle speed

TABLE 3.3

ENGINE MAP DATA

ENGINE MAP DATA TABLE ORGANIZATION			
DATA TABLES		CONDITIONS	
TORQUE DATA TABLE	THROTTLE DATA TABLE	SPEED SETTING (%)	THROTTLE POSITION (%)
T00	P00	0	0
T01	P01	0	10
T02	P02	0	20
:	:	:	:
T09	P09	0	90
T0A	P0A	0	100
T10	P10	10	0
T11	P11	10	10
:	:	:	:
T19	P19	10	90
T1A	P1A	10	100
T20	P20	20	0
:	:	:	:
:	:	:	:
TAA	PAA	100	100

is reached. The data organization is shown in table 3.3.

The data is organized in this manner in order to facilitate the movement of the correct blocks of data for use in calculating the throttle position based on speed and torque. The method by which the data is moved and the throttle position calculated is shown in figure 3.10 on the next page.

As can be seen from table 3.3, the torque and throttle position data can be divided up into eleven subsets, each of which corresponds to a particular vehicle speed. As an example, assume that the desired

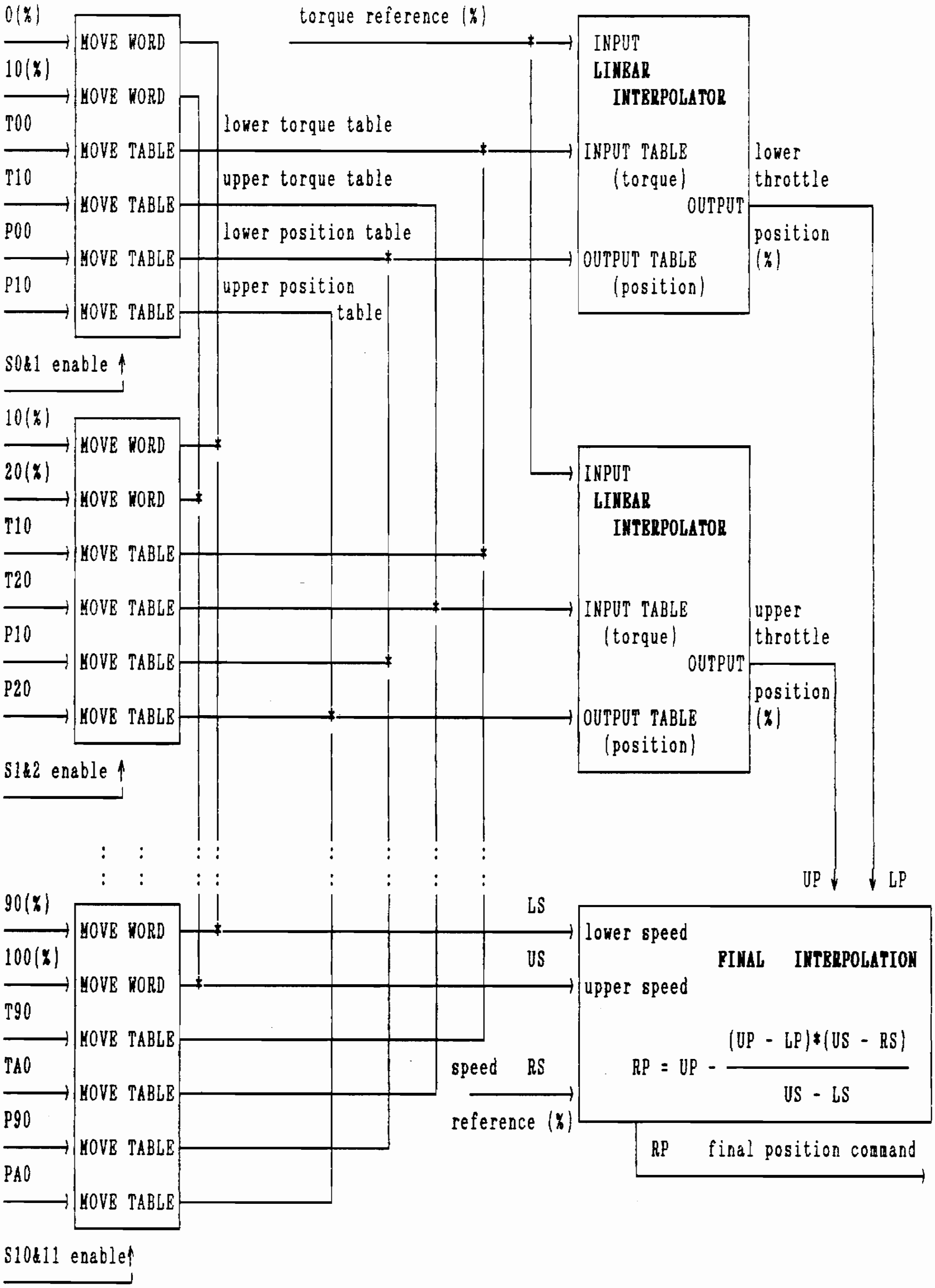


FIGURE 3.10

THROTTLE POSITION CALCULATION

vehicle speed is ten percent. In order for the torque to be "T21" percent, then the throttle position must be set at ten percent (P21). Remember that "T21" is the amount of torque determined during the engine map procedure. This is exactly how the code shown in figure 3.10 determines the required throttle position. As shown in the figure, linear interpolators are used, which give straight line approximations to the actual characteristic curves.

Inspection of figure 3.10 will show that there are eleven sets of "MOVE WORD/TABLE" blocks, one for each speed point. Each of these blocks actually consist of three CBL IMOV00 blocks, which move the contents of memory from one location to another. The number of words (one word is equal to two bytes) moved is a parameter of the IMOV00 block. Using a speed range of zero to ten percent as an example, the first IMOV00 block moves the constant numbers zero and ten into the variables for the "lower speed point" and "upper speed point", respectively. The number of words moved is four, since these are floating point numbers (a floating point number requires two words). The second IMOV00 block moves the torque values for "T00" through "T0A" and "T10" through "T1A" to the locations used by the lower and upper speed point interpolators. The number of words moved in this case is 88. Finally, the third

IMOV00 block moves the same quantity of the corresponding throttle position values for the zero and ten percent speed point to the interpolator variables. (The throttle position values are the same for all speed points: zero through one hundred percent in ten percent increments. Throttle position data sets for each speed point are included for reasons of consistency, flexibility, and simplicity). Figure 3.11 summarizes the actions of the first set of IMOV00 blocks. The other ten sets write to the same variable locations shown on the right when they are enabled.

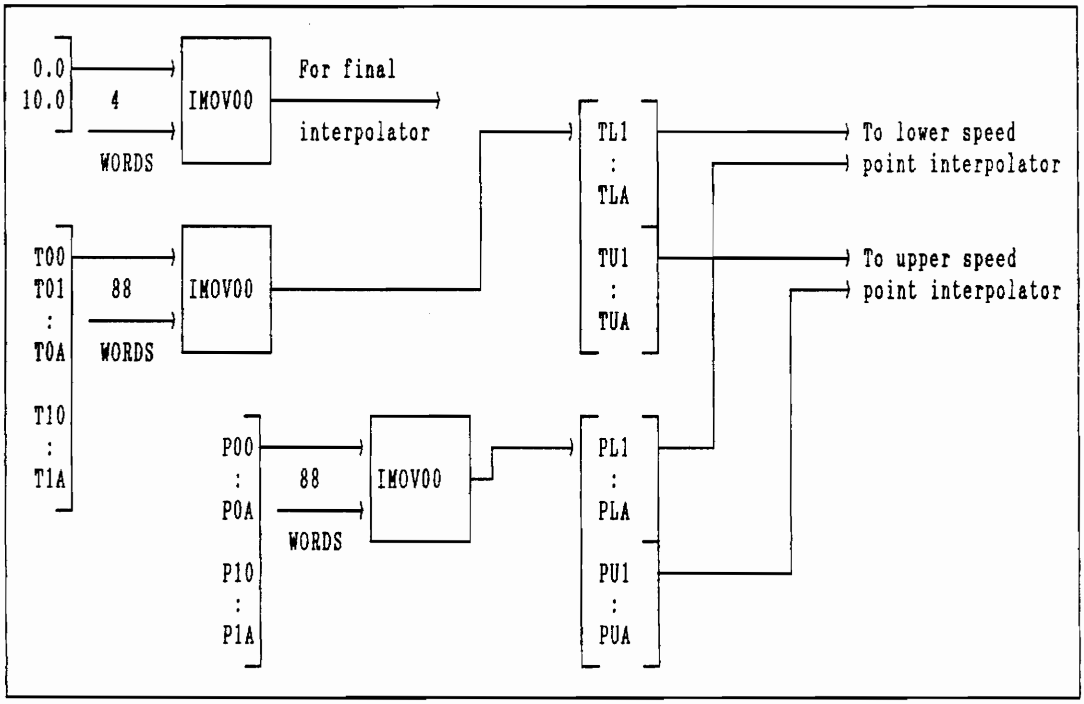


FIGURE 3.11

SPEED POINT DATA MOVES

Only one set of "IMOV00" blocks are executed by the processor during a cycle. If the speed reference changes from 9.9 percent to ten percent, then the first set of IMOV00 blocks are disabled and the second set of blocks are enabled. When this takes place, the variable tables (180 words) for the linear interpolators are updated with the new data set during one cycle of the processor. The logic signals which control the enable lines of the IMOV00 blocks are shown in table 3.2.

Figure 3.12 on the next page shows a typical relationship between the vehicle torque and throttle position. This figure is used to show how the interpolators in figure 3.10 are used, and how they work.

The interpolators are table driven CBL blocks which perform straight line approximations on the input, based on both the input and output tables. The CBL block reads the input variable (in this case, the torque) and determines the two input table points which are greater than and less than the input value. The block then calculates exactly where the input is in relation to the two input table points, and applies the resulting ratio to the equivalent output table points. The result is throttle position.

Inspection of figure 3.12 will show that at point "a", the torque is 55 percent and the throttle position is at 30 percent. The vehicle speed is ten

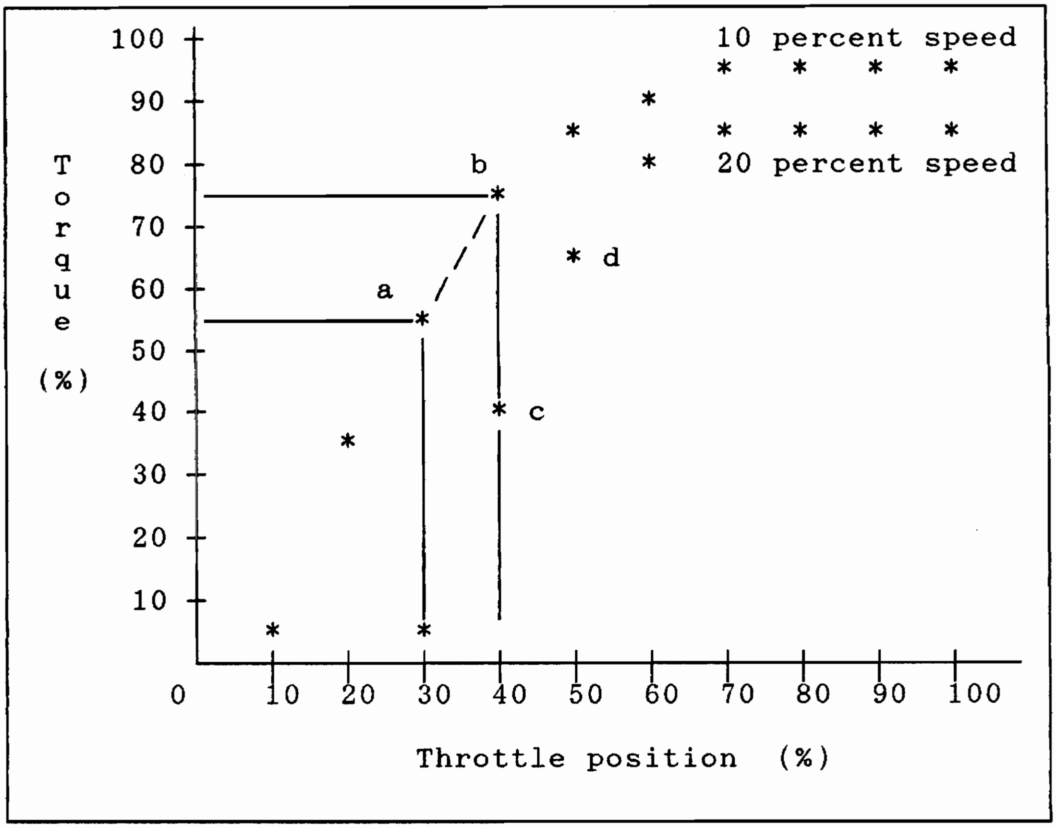


FIGURE 3.12

VEHICLE TORQUE VERSUS THROTTLE POSITION CURVES

percent. The CBL interpolator block first finds the ratio (RL) based on the actual torque input (T), or

$$RL = (T - Ta)/(Tb - Ta). \tag{3.9}$$

The block then finds the throttle position PL based on RL, Pa, and Pb, or

$$PL = RL*(Pb - Pa) + Pa. \tag{3.10}$$

The CBL interpolator block actually finds the throttle position by solving

$$PL = \frac{T - Ta}{Tb - Ta} * (Pb - Pa) + Pa. \tag{3.11}$$

For the vehicle speed of twenty percent shown in figure 3.12, the equation for throttle position is

$$PU = \frac{T - Tc}{Td - Tc} * (Pd - Pc) + Pc. \qquad (3.12)$$

Table 3.4 defines all of the parameters used in the last two equations. It also shows the relationship with the data table mnemonics used previously. The actual values shown are based on the curves of torque versus throttle position and an actual torque input value of 60 percent. For the lower speed point of ten percent, the throttle position calculated from equation (3.11) is 32.5 percent. The throttle position for the upper speed point is 48.0 percent.

TABLE 3.4

TORQUE, POSITION, AND SPEED EXAMPLE

	Lower speed point = 10 %			Upper speed point = 20 %		
	Equation parameter	Data table mnemonic	Value (%)	Equation parameter	Data table mnemonic	value (%)
From torque table	Ta	T13	55	Tc	T22	40
From torque table	Tb	T14	75	Td	T23	65
From position table	Pa	P13	30	Pc	P22	40
From position table	Pb	P14	40	Pd	P23	50
Actual torque	T		60	T		60
Calculated position	PL		32.5	PU		48

Actual speed reference RS = 17 %
Final throttle position RP = 43.35 %

As with the torque, the speed reference will rarely be at one of the ten percent speed increments. For this reason, the system must interpolate between the throttle positions found for the upper and lower speed reference points. This interpolation is shown in figure 3.10 in the lower right hand corner, marked the "Final Interpolation". As with the CBL interpolator block, the final interpolation formula is based on the fact that the ratios of position and speed are equal, or

$$(UP - RP)/(UP - LP) = (US - RS)/(US - LS). \quad (3.13)$$

Solving for RP, the final position reference, gives

$$RP = UP - \frac{UP - LP}{US - LS} * (US - RS), \quad (3.14)$$

which is the same equation shown in figure 3.10. As can be seen from table 3.4, the result of the calculation gives a throttle position of 43.35 percent. This can be confirmed from figure 3.12. A torque-position curve for a speed of seventeen percent would be placed about three quarters of the way between the ten and twenty percent curves. It can be seen that the intersection of a horizontal line at 60 percent torque with the seventeen percent torque versus position curve, will give a throttle position of about 43 percent.

The result of equation (3.14) is the throttle position reference that is switched into the indexer position code when the predictive control is active. All of the code for the predictive control, from the table "moves" through the final interpolation, is executed every 100 milliseconds. Each calculation is based on the present speed and torque reference at the time of execution.

There will be errors in the engine map characteristic data, along with errors in the three interpolations performed. This should not be of any great consequence, however, because the idea is to position the throttle so the speed of the vehicle will be close to the desired speed. Once the actual speed is close enough, the predictive control will be disabled and the speed regulator will position the throttle in order to obtain a vehicle speed equal to the reference. The point at which the predictive control is enabled and disabled can be adjusted, based on the accuracies of the engine map data.

Scaling the Speed Reference

In order to simplify the coding and maintain consistency when different vehicles are tested, all vehicle related parameters are converted to percent. With most of the code in the throttle controller the scaling is quite simple. However, in order to simplify the engine map procedure and the predictive control, the vehicle speed range must always be based on a reference that is between zero and 100 percent. This is true even though vehicle base speed may be non zero (A non zero minimum speed is necessary for testing vehicles with a manual transmission). For instance, in testing the third gear of a vehicle with a manual transmission, the minimum speed may be 30 miles per hour and the maximum speed 60 miles per hour. However, in detecting the speed range for the predictive control, the corresponding speed range must be from zero to 100 percent. The conversion of the speed reference (in percent) is based on

$$RTBL = \frac{100}{MXGS - MNGS} * (SPRF - MXGS) + 100. \qquad (3.15)$$

Where,

RTBL = Speed reference for predictive control table (%).

MXGS = Maximum speed for the gear being tested (%).

MNGS = Minimum speed for the gear being tested (%).

SPRF = Speed reference (%).

The speed reference (SPRF) is scaled in percent, zero to 100% corresponding to 0 to maximum vehicle speed in miles per hour. From equation (3.15) it can be seen that when the speed reference is equal to the maximum speed for the gear being tested, the predictive control reference is equal to 100. When the speed reference is equal to the minimum speed, the predictive control reference will be zero.

The engine map procedure requires a conversion in just the opposite sense as equation (3.15). During the engine map procedure, the initial reference developed is scaled in the same sense as "RTBL". The engine map procedure must scale this reference in miles per hour before sending it to the dynamometer, where the speed of the vehicle is controlled. The equation for this conversion is found easily by solving for "SPRF" from equation (3.15) and then scaling to miles per hour. The resulting equation is

$$SPDR = \left(\frac{MXGS - MNGS}{100} * RTBL + MNGS \right) * \frac{MXVS}{100} . \qquad (3.16)$$

The new variables in equation (3.16) are "MXVS", which is the maximum vehicle speed in miles per hour, and "SPDR" which is the speed reference in miles per hour. "SPDR" is sent to the dynamometer over the CSF during the engine map procedure.

This completes the description of the throttle predictive control and Chapter Three (Materials and Methods). The next chapter presents the methods of testing the throttle control speed regulator and predictive control along with the results of the tests. The final chapter presents possible alternatives and improvements to the system based on the results of the tests. The final section is a summary of the predictive control and the test results.

CHAPTER 4

TESTING

Testing of the predictive control system took place in three phases. The first phase was a system test of the software and selected items of hardware supplied by General Electric. This test took place in August of 1987 before the equipment was shipped to the wind tunnel site. The second phase was on site testing for one week, which took place in June of 1988. Due to time limitations and scheduling conflicts with Ford, General Electric, and other contractors, it was not possible to complete all the testing that was required for this thesis. For the above reasons a third phase of testing was performed by the author. The third phase consisted of a software simulation of the whole system in a Distributed Micro Controller (DMC). This test included simulating the master control DMC for the road load equation and inertia compensation, the analog torque regulator, the dynamometer, and the vehicle.

Below is a short description of the phase one system test. Phase two and three are described in more detail in sections 4.1 and 4.2 respectively.

The primary purpose of the system test (phase one) is to verify the integrity and functionality of the software and hardware that is supplied by General

Electric. A system test is performed on all but the simplest jobs supplied by General Electric. The hardware included in this system test included the following:

1. Master control DMC.
2. Throttle control DMC.
3. CSF communications link between the two DMC's.
4. Operator station push button module.
5. Operator station video display.
6. Throttle indexer, driver and motor.
7. Throttle position pulse tachometer.

The author had sole responsibility for testing the throttle control DMC, its software, and the stepping motor system. It was necessary to work with the two engineers that were involved with the master control DMC. This cooperation was needed in order to prove both the hardware and software functionality between the two DMC's.

All of the major software subsystems in the throttle control DMC were tested. The systems tested included the indexer control, speed regulation, torque regulation, predictive control, mode selection and switching, operator data entry and control at the push button station, and data display for the video system. Speed and torque feedback for the regulators were simulated in a very simplistic manner to prove that the code worked functionally. The simulation was kept simple because of time constraints, and because testing for this thesis was expected to take place on site once the equipment was installed. The next section describes the testing performed on site.

4.1 On Site Testing

On site testing took place in June of 1988 for one week. Only one week was available for testing due to work constraints General Electric. Another General Electric engineer, John Carlton, accompanied the author to the site in order to assist in solving problems with the dynamometer and master control DMC. Also of assistance was a General Electric field service engineer, Ron Adams, who was assigned to the Ford project.

Before on site testing would take place, it was desirable that the throttle speed and torque regulators would be tuned and all the "bugs" in the basic system would be worked out. Given the above, it would only be necessary to test and debug the engine mapping procedure, fine tune the speed regulator, and test the predictive control. As it turned out, Ford had gotten a vehicle onto the rolls just three days before the author's testing was to take place. The only work that had been done on the throttle control DMC was to obtain position mode control of the throttle. The dynamometers had been run in both speed and torque mode, but response time was only on the order of one radian per second. A faster response time could not be obtained because of instabilities caused by more mechanical natural frequencies in the system than was expected. The author was not involved in this part of the system at all.

The vehicle used for testing the throttle controller was a 1987 front wheel drive Ford Taurus sedan with 900 miles on the odometer. The engine was a six cylinder with an automatic transmission. All of the testing performed was in manual mode, with control from the operator station in the control room.

Section 4.1.1 describes the test plan used for on site testing.

4.1.1 ON SITE TEST PLAN

The test plan below was devised based on the conditions and previous work that had been done already. Note that half of the plan consists of necessary set up work before the engine map and predictive control could be tested.

1. Check for proper operation of indexer initialization.
2. Perform the full and idle throttle position procedure and check for proper storage of parameters.
3. Check throttle position mode. Check for proper reference and feedback scaling.
4. Check and record position control response and accuracy.
5. Set up vehicle and regulator parameters from the operator station. Save in table 1.
6. Run the vehicle with the dynamometer in torque mode and the throttle controller in position mode.
7. Check for proper scaling of torque and speed feedback and references.
8. Determine maximum and minimum torque for

use in scaling and for the engine map procedure. For this test, the dynamometer is speed regulated with the throttle in position mode. For maximum torque, the dynamometer will regulate the vehicle speed to one mile per hour, with the throttle increased towards 100%. Minimum torque is determined by forcing the vehicle speed towards maximum with the throttle at zero percent.

9. Check and record vehicle speed response with the dynamometer in torque mode, and the throttle in position mode. Use various step sizes, including zero to 100% throttle position. Repeat with various torque settings. The purpose of this test was to obtain some idea on the characteristics of the vehicle itself.

10. Test and tune the throttle speed regulator. Record speed regulator response. Use various torque settings.

11. Test and debug the engine map procedure. Check that the data is stored properly.

12. With the dynamometer in torque mode and the throttle controller in position mode, check for repeatability of the engine map data

collected in step eleven.

13. Enable the predictive control. Test and debug the predictive control.
14. Record the response to various speed reference step and ramp changes. Record response to torque disturbances. Perform tests with the dynamometer in manual torque mode, manual torque mode with inertia compensation, and with road load simulation.

Section 4.1.2 describes the tests that were performed, problems encountered, and results that were obtained.

4.1.2 ON SITE TEST RESULTS

The test plan was followed fairly well, but it was not completed. System problems and delays caused by multiple contractors being on site precluded the completion of all the tests in the plan. The following paragraphs will briefly discuss the tests performed and the results, including some of the problems encountered.

Items one through six of the test plan went very smoothly. The indexer performed well, with only one minor software change. Position control of the indexer and stepping motor was very accurate and fast. However, due to a problem to be described later, the results on the performance of the indexer and stepping motor had to be discarded. There was no time for recording further tests after a temporary fix was implemented.

In checking the speed feedback, it took four hours to find that the pulse tachometer inputs for one channel were backwards. The fault was with the standard schematic drawings for the input card, which had the terminals mislabeled! It was also found at this point that the torque feedback was not very steady. Inspection of figure 4.1 shows that the unfiltered torque feedback from the load cell fluctuated by 140 lb-ft (4.8%) at a frequency of 2.5 hertz. The filtered feedback used by the throttle controller was fairly

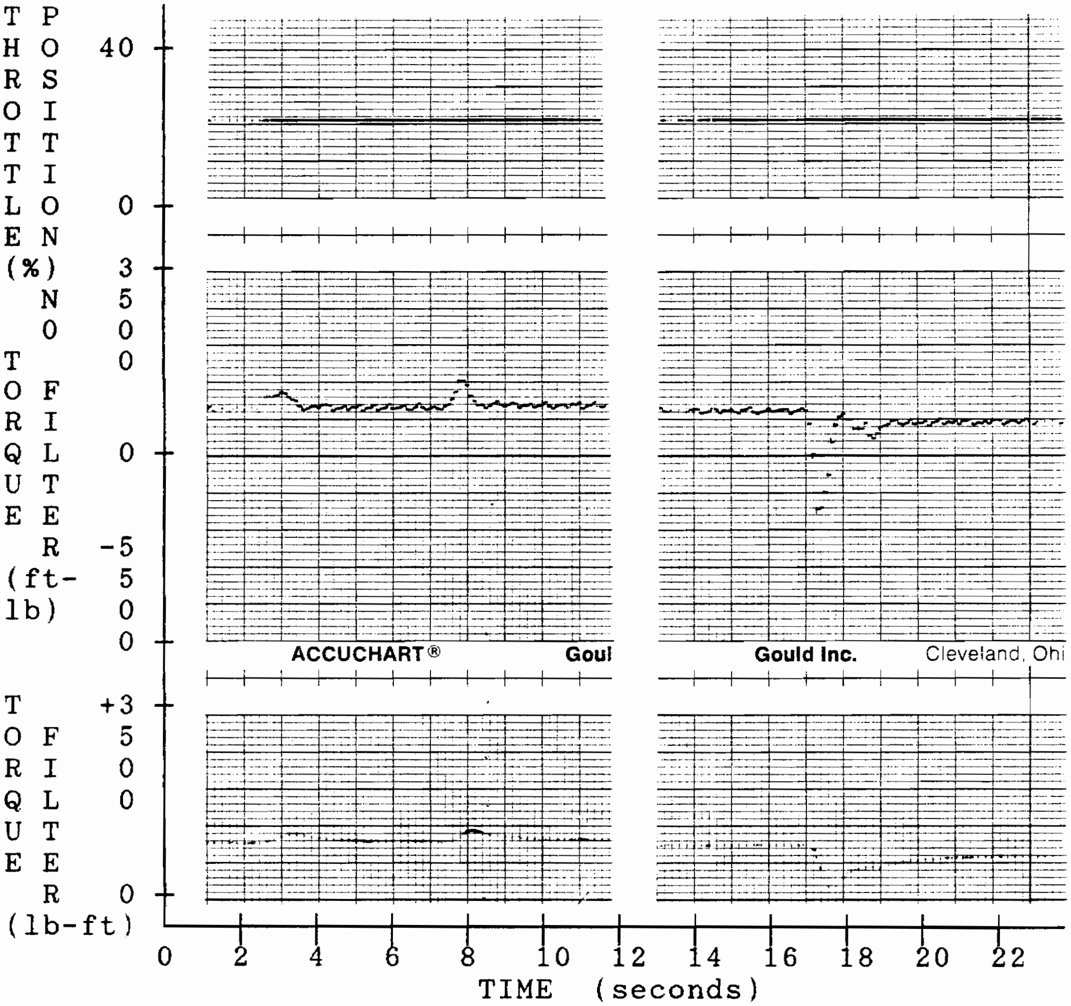


FIGURE 4.1

ON SITE TORQUE FEEDBACK

steady, but the effect on the response to sudden changes in torque can be seen by both traces. The lag in the filter was set at .8 seconds. For both traces of Figure 4.1, the dynamometer was controlling the speed while the throttle was in position control. The disturbances in torque for the first trace were caused by a change in throttle position with the speed held constant.

The second trace shows a torque disturbance due to a change in speed from the dynamometer with the throttle held constant.

The test to determine maximum and minimum torque of the vehicle was very interesting, since it was required to push the vehicle toward its operating limits. The maximum torque test was performed with the dynamometer in speed mode and the throttle controller in position mode. Vehicle speed was fixed at ten percent speed (maximum speed was fixed at 80 miles per hour, which is fairly low for a six cylinder Taurus. This was done in the interest of safety). The throttle was then increased slowly from zero. At 35 percent throttle, with speed still at ten percent, the wheels started to squeal on the rolls. The throttle was taken up to 67 percent where it was necessary to abort the test. At ten percent speed and 67 percent throttle, the torque produced was 3600 lb-ft. With a roll radius of 2.25 feet, the force produced was 1600 pounds. Being conservative in regards to the engine mapping procedure, the maximum torque was set at 2925 lb-ft (1300 lbs).

The minimum torque test was started with the vehicle at 65 miles per hour, and the throttle at 30 percent. With the vehicle speed held at 65 miles per hour by the dynamometer, the throttle was reduced to zero percent. The dynamometer was required to produce

245 lb-ft (109 lbs) of torque in order to force the vehicle wheels to turn at 65 miles per hour. The minimum torque used for the engine mapping procedure was set at -245 lb-ft (-8.3 percent of maximum).

Due to time constraints, step nine of the test plan was not performed. This was the test to record engine speed response with the dynamometer in torque mode and the throttle in position mode.

After an unstable start, the throttle speed regulator was tuned for a very acceptable response. Figure 4.2 shows the vehicle speed response to a small step change in speed reference. The first trace shows a step increase from 47 to 50 percent speed, while the second is for a decrease from 50 to 47 percent. The third trace is for a larger step, from 45 to 50 percent. Regulation of the torque by the dynamometer did not include inertia compensation. The torque was set at a low value, about four percent (torque that the engine was required to produce). Note that the first trace shows a nearly critically damped response, while the second trace shows undershoot. The third trace shows overshoot with the larger step change. All the responses are with the same regulator parameters. The recordings in figure 4.2 demonstrate the problem with a straight speed regulator for the vehicle throttle: different speed responses which are dependent on the operating conditions.

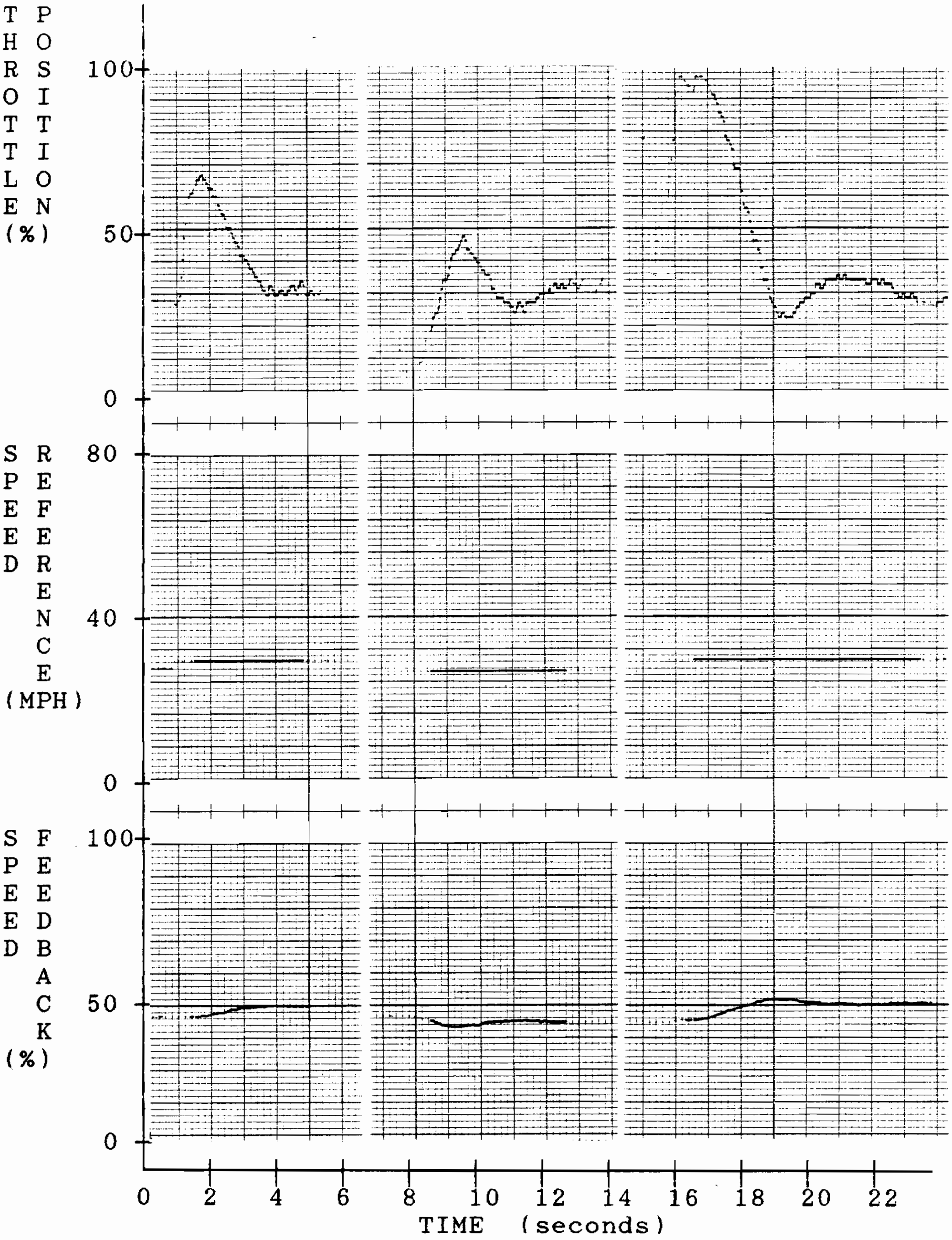


FIGURE 4.2

ON SITE SPEED REGULATOR RESPONSE

The values of the regulator parameters are shown below;

Regulator gain, Ksr = 2.5

Regulator lead, tld = 5.0 seconds

Feedback lag, tfg = .95 seconds

Feedback lead, tfd = 1.2 seconds

During the speed regulator tests it was found that the calibration of the throttle was slowly changing over time. After about a half hour of continuous throttle movement, it was found that the position command was ten to fifteen percent more than the position feedback! It was first thought that the tachometer shaft was slipping in relation to the stepping motor shaft. As it turned out, the closed loop position control in the indexer had a feature that was causing the problem. If the torque was too great, the motor would miss pulses from the indexer during high acceleration rates on the stepping motor. Since the indexer reads the tachometer feedback, it can sense this condition and correct for it. However, if the stepping motor is not able to obtain the desired position, the indexer will assume a stall condition, and reset the absolute zero position so that the feedback will match the reference.

The mechanism that was used to drive the vehicles' acceleration pedal was designed such that only one third of a revolution was required to go from idle to full throttle position. As it turned out, both the torque required to move the throttle and the acceleration rates for the indexer was too great for the stepping motor. This caused the motor to miss pulses from the indexer. As long as the error was not too great, this problem had no effect on the speed regulation. This is true because the integrator does not care what its output is, just as long as the speed feedback matches the reference.

The problem was reduced to acceptable levels for the tests by reducing the acceleration rate used by the indexer. This had a detectable impact on the response of the throttle position control. As indicated at the beginning of this section, recordings of the new response were not obtained due to lack of time. Possible methods of permanently resolving this problem will be discussed in chapter five.

The engine map procedure would have worked fine if testing had been with a vehicle with a manual transmission. With an automatic transmission, it was found that when the vehicle speed was held constant by the dynamometer and the throttle was increased towards 100 percent, the engine RPMs would become excessive. An emergency stop of the system was required twice during the engine map procedure. The automatic transmission was down shifting into first gear, but since the speed could not increase it would stay in first gear. After the vehicle shifted into first, the engine RPM would approach red line, even though the torque was not excessive. The throttle controller monitors vehicle torque and speed to maintain safe conditions, but not engine RPM. This problem was not foreseen in the initial design of the system.

Engine RPM is available, and can be brought into the throttle controller quite easily. However, the necessary modifications would have taken too long for the remaining time on site. Instead, the engine mapping procedure was run manually in order to collect the required data for the predictive control. The engine map data is shown in table 4.1 below. The data was manually entered into the throttle control DMC for use

TABLE 4.1

ENGINE CHARACTERISTIC DATA FOR TESTING

	TORQUE VALUES IN TABLE ARE IN PERCENT										
THROTTLE POSITION	SPEED 0%	SPEED 10%	SPEED 20%	SPEED 30%	SPEED 40%	SPEED 50%	SPEED 60%	SPEED 70%	SPEED 80%	SPEED 90%	SPEED 100%
0%	12.2	2.0	-1.9	-3.7	-4.8	-6.1	-6.5	-7.5	-9.1	-10.0	-11.0
10%	20.4	9.8	5.8	1.1	-0.9	-2.7	-4.4	-5.1	-6.3	-7.1	-8.3
20%	77.5	48.5	22.5	18.2	15.0	7.9	7.0	4.9	3.2	1.5	0.0
30%	121.6	85.7	40.3	30.7	23.7	17.3	15.0	13.2	10.3	9.2	8.2
40%	133.2	106.3	58.5	38.5	33.8	23.0	17.8	16.5	14.5	13.2	12.5
50%	142.5	115.8	67.1	43.8	40.1	27.4	19.2	18.1	16.3	15.4	14.4
60%	145.7	119.2	95.6	59.6	42.6	36.0	28.4	20.4	18.6	17.1	16.5
70%	150.0	122.3	105.4	60.2	54.5	37.3	35.1	33.2	31.7	30.3	29.2
80%	150.0	122.3	105.4	60.2	54.5	50.6	48.2	33.2	31.7	30.3	29.2
90%	150.0	122.3	105.4	60.2	54.5	50.6	48.2	33.2	31.7	30.3	29.2
100%	150.0	122.3	105.4	60.2	54.5	50.6	48.2	33.2	31.7	30.3	29.2

by the predictive control.

A plot of the collected engine characteristic data is shown in figure 4.3. Between zero and ten percent speed (zero to eight MPH), the vehicle was always in first gear with the throttle between zero and 100% (actually, we did not go to full throttle since it was not desirable to go much beyond 100 percent torque). Twenty percent speed shows a shift from second gear to first right around 50 percent throttle. At 50 and 60 percent speed (40 to 48 MPH) a shift from third to second gear can be seen at 50 percent throttle, and then a shift to first at 70 percent throttle. From 70 and 100 percent speed the vehicle was shifting into second gear between 60 and 70 percent throttle.

It was between 30 and 60 percent speed that the engine RPMs would become excessive. In running the engine map procedure manually, the vehicle was not held at these points very long - just long enough to read the torque. The higher throttle positions where not checked at these speeds since it was known that the vehicle could not deliver any more torque.

The final and main test to perform was the predictive control. This test was attempted the day after the engine characteristic data had been collected. Before the predictive control test could be performed,

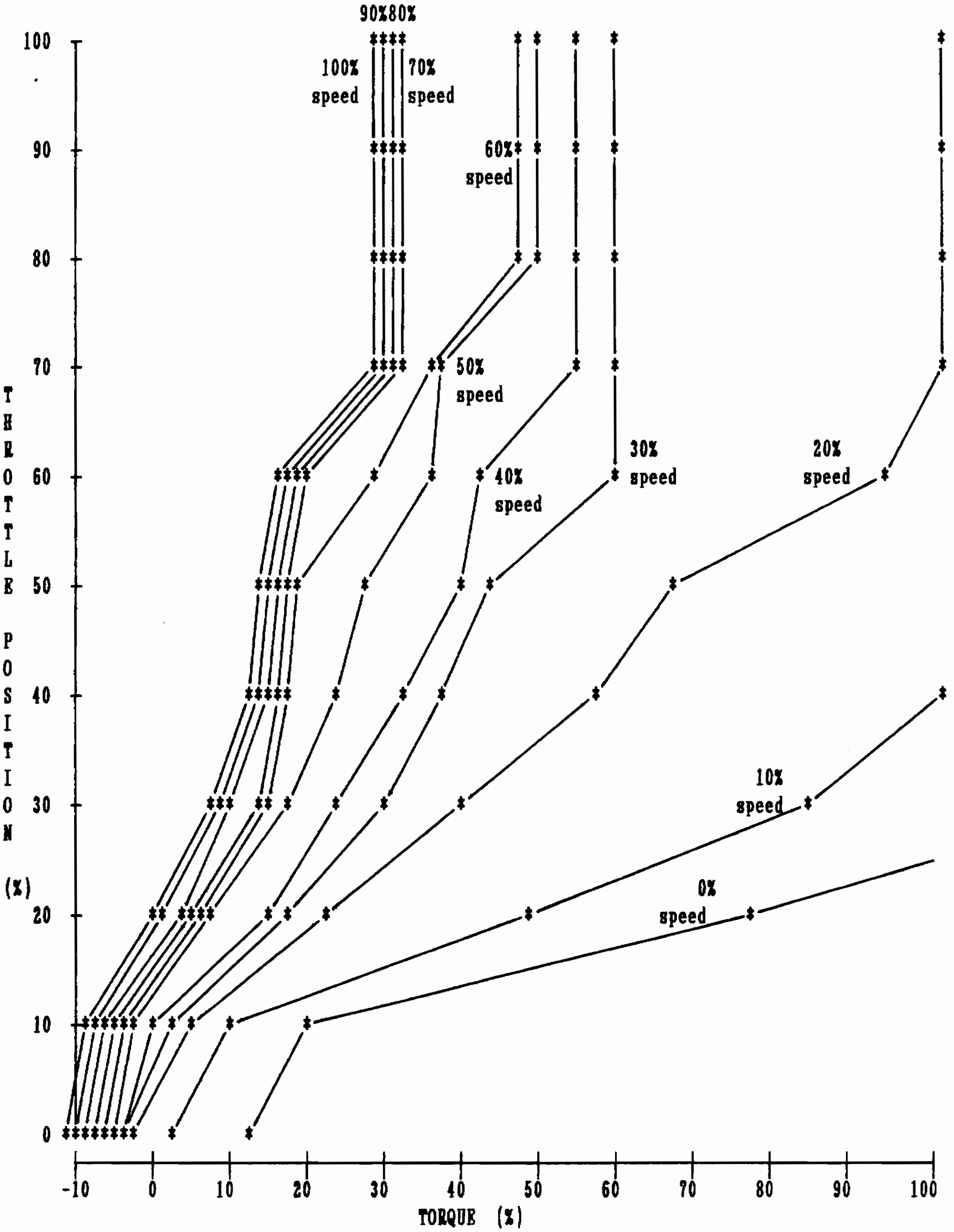


FIGURE 4.3

<u>PLOT OF ENGINE CHARACTERISTIC DATA</u>

it was necessary to remove the vehicle from the wind tunnel so other unrelated work could be done. When everything was back together the next day, it was found that it was nearly impossible to set the idle and full throttle positions to exactly the same points that were used when the engine map procedure was run. This was a problem that was not foreseen in the initial design of the system. Again, possible solutions to this problem will be discussed in chapter five.

Instead of rerunning the engine map procedure again, the idle and full throttle positions were set as close to the original points as possible. It was found that at some points the actual throttle position was less then the predicted positions, while other points were greater than the predicted positions.

The basic software for running the predictive control worked fine, but because of the miscalibration of the throttle, the predicted throttle position was less than that required to obtain the desired speed. Several speed-torque combinations were found where the predicted throttle position was close to or greater than what was actually required. It was at these speed and torque ranges that the predictive control was tested.

Figure 4.4 shows the response curve for the pure speed regulator, while figure 4.5 shows the response with the predictive control enabled. Both

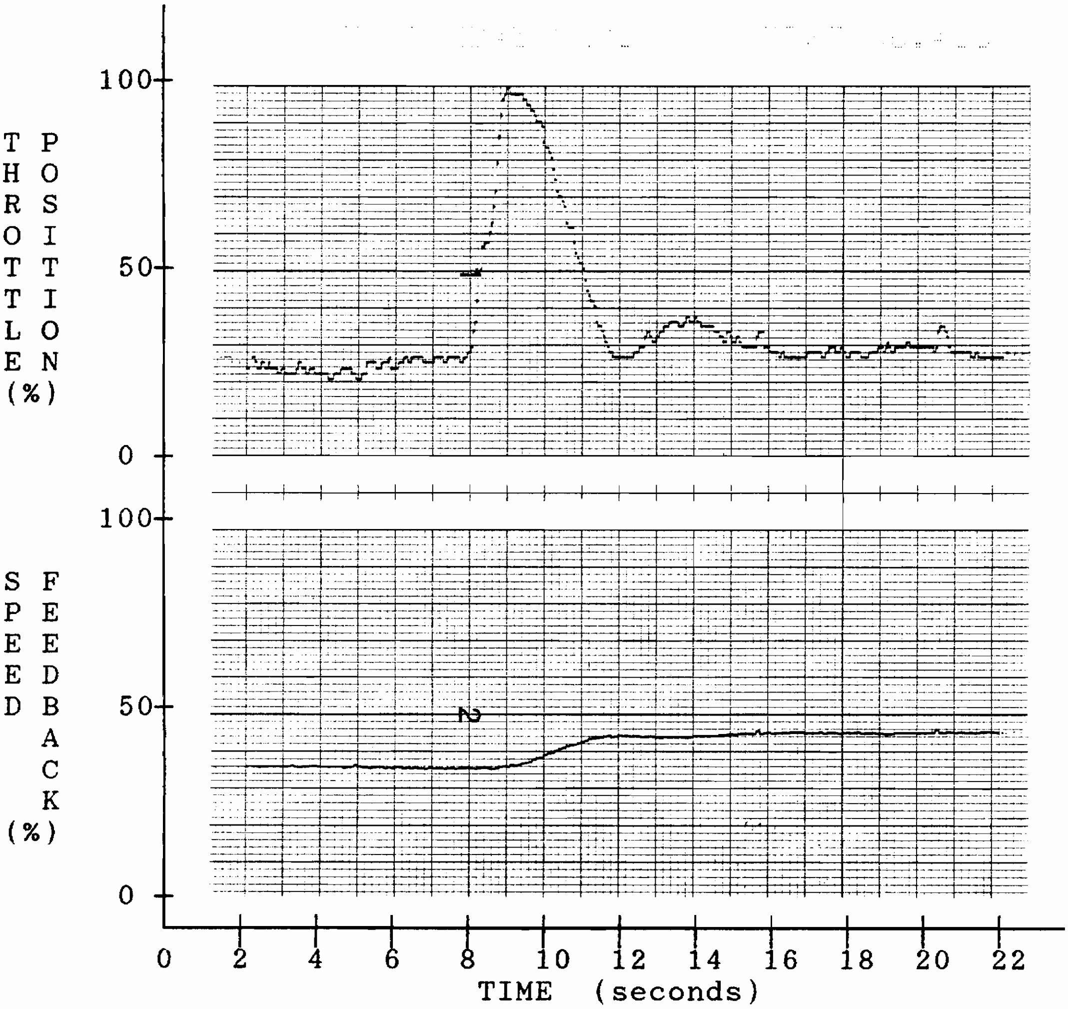


FIGURE 4.4

PREDICTIVE CONTROL TEST:

SPEED REGULATOR RESPONSE

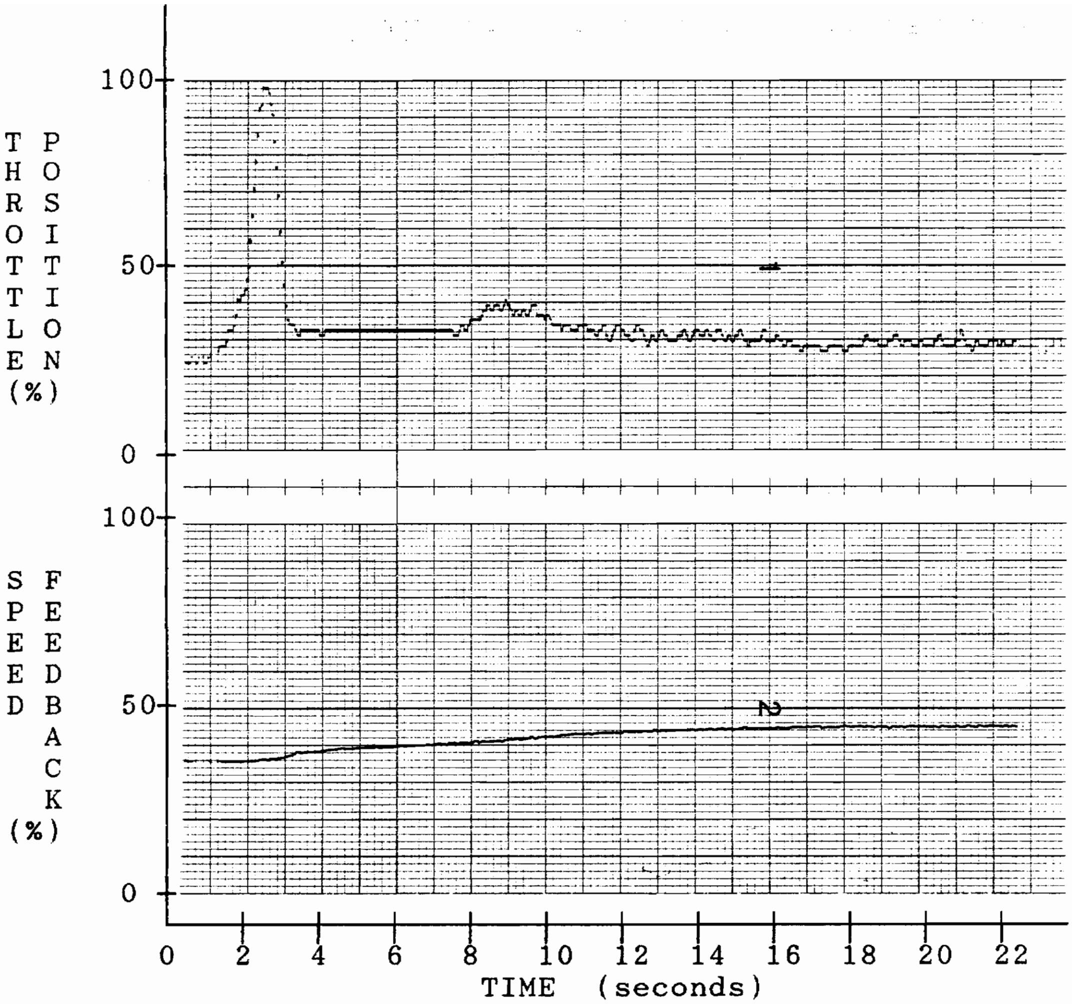


FIGURE 4.5

PREDICTIVE CONTROL TEST:

PREDICTIVE CONTROL RESPONSE

traces are for a reference step change of 40 to 50 percent speed. The dynamometer was set to regulate the vehicle torque to plus eighteen percent (the convention throughout this paper has been: positive torque means the vehicle engine is supplying power to the dynamometer and negative torque means that the dynamometer is supplying power to the vehicle). The dynamometer did not include any inertia compensation or losses.

Figure 4.4 shows a faster response than with the predictive control, but there is a little undershoot before the speed moves to the desired 50 percent. Also, the response is not the same as that of figure 4.2 where the speed and torque settings were different. When the predictive control was enabled, the speed moved at a fairly steady rate to the desired speed reference. The only bump is at the very beginning just before the predictive control sensed a large enough error. For this case, the predictive control was set to take over when the speed error was greater than seven percent, and the speed regulator takes back control when the speed error was less than five percent. It would be a simple matter to reduce the amount of speed error required before the predictive control takes over in order to decrease the bump at the start of a speed reference change. This would also reduce the throttle action. The reduction can be seen by inspection of figure 4.5.

It can be seen in figure 4.5 that the predicted throttle position for 50 percent speed is about 32 percent. This is in contrast to the required throttle position during speed regulation of around 29 percent. The speed regulated throttle position of 29 percent versus the predicted 32 percent is due to not being able to set the idle and full throttle positions to the same points that were used when the engine map procedure was run. Referring to figure 4.3, the engine characteristic curves do indicate that the throttle should be around 32 percent.

The subject of throttle calibration in regard to the predictive control will be covered in more detail in section 4.2.2 (simulation test results) and in chapter five.

4.2 SOFTWARE SIMULATION TEST

The on site testing at the Ford wind tunnel was somewhat limited. There was not enough time to run the predictive control under different loads and various speeds. The dynamometer was strictly torque controlled with no inertia or loss compensation. The on site tests did not include running the dynamometer with the road load equations. For these reasons, it was necessary to perform more testing in the form of software simulation. Software simulation was required because the actual wind tunnel would not be available again within the time frame required for completion of this thesis.

In order to perform the software tests, it was necessary to write the software to simulate the dynamometer torque regulator, the dynamometer, and the vehicle. As with the original throttle control software, the simulation code was written in General Electric's CBL language for the DMC. The simulation code was combined with the original throttle control code and then downloaded into a DMC at General Electric's Salem plant. The DMC was one of the many available for testing at General Electric. For this test, all that was required was a processor card, a memory card, and an analog output card.

For the throttle control speed regulator and the predictive control the original code, as shipped to site, was used for the simulation. However, all the extraneous code that did not directly apply to the speed regulator and the predictive control was stripped out. This was done so that the segment scan time for the torque regulator could be decreased to around ten milliseconds.

The next section, 4.2.1, will cover the methods used to simulate the different parts of the system. This will be in the form of block diagrams. The final section of chapter four will discuss the test results using the simulation, and compare them to the on site test results.

4.2.1 THE SIMULATION CODE

The simulation code is comprised of three parts as shown by the top three blocks of figure 4.6. The throttle control software, the bottom block in the

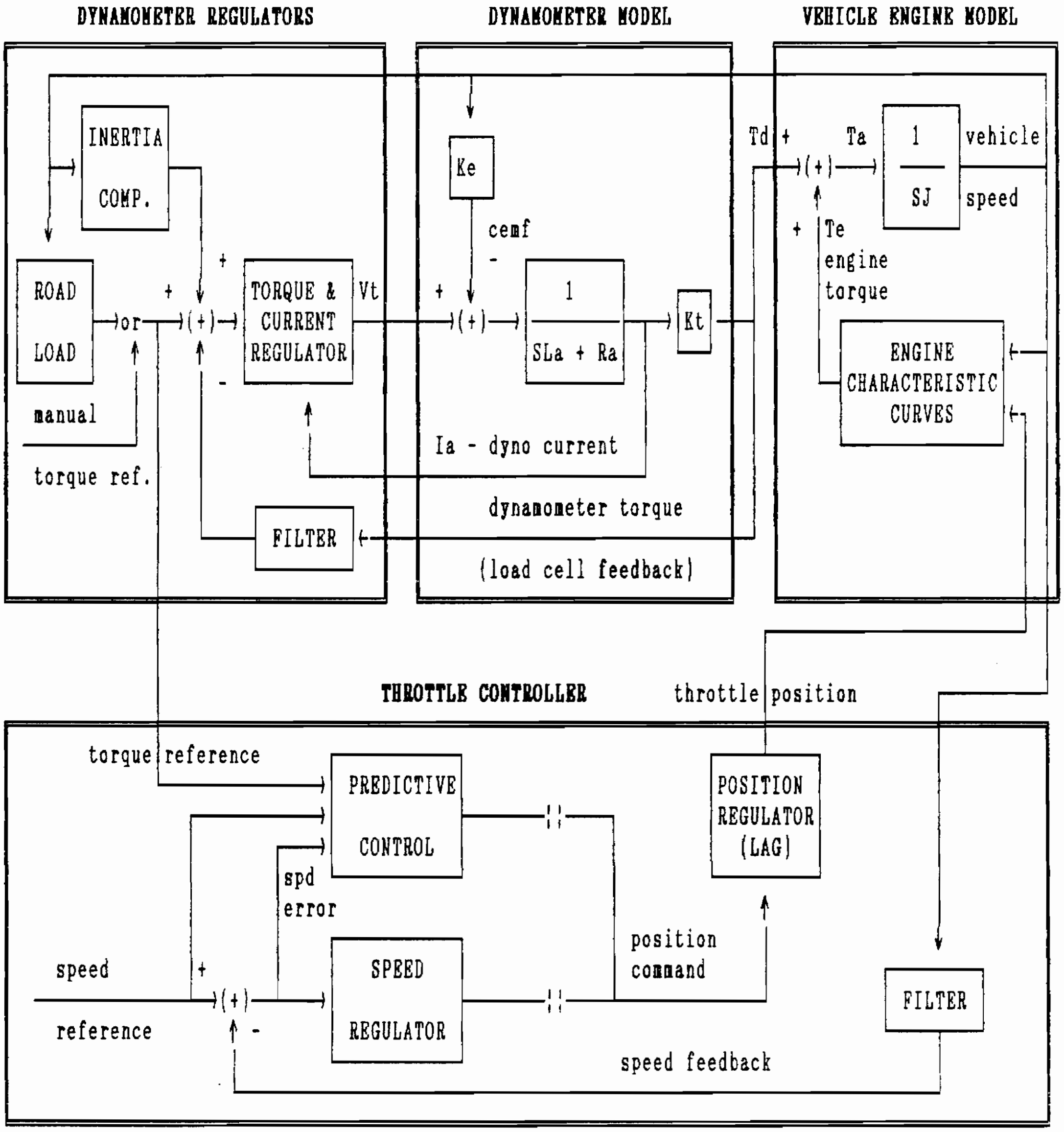


FIGURE 4.6

SIMULATION DIAGRAM FOR TESTING

figure, is the code that was used for the site. The indexer or stepping motor was not available, so the position regulator was simulated as a simple lag. This approximation was sufficient, as the system on site reacted as a simple lag.

The dynamometer is modeled after a simple DC motor with a fixed field. This model is rather simple since it leaves out a lot of the torsional spring constants between the motor shaft and the rolls. Also, it does not include any friction or windage losses. Load cell feedback is taken as simply the armature current times the torque constant of the motor. The actual transfer functions involved with the torque feedback were not included as this was not necessary for the purpose of the testing.

The most important factor in the dynamometer model was to obtain the effect of vehicle speed on the CEMF of the dynamometer (which has an effect on the torque). The purpose of this was to show the interaction between the dynamometer regulator and the throttle speed regulator. This will be covered in more detail in section 4.2.2, Simulator Test Results.

The parameters for the dynamometer model were set very close to the actual system. Table 4.2 shows the model parameters used for the simulation.

The vehicle is simulated by integrating the

TABLE 4.2

DYNAMOMETER PARAMETERS FOR SIMULATION

rated armature current (Ia)	390 Amps
rated motor terminal volts (Vt)	425 Volts
rated torque (Td)	8890 Lb-Ft
rated motor RPM (Vrpm)	625 RPM
rated roll speed (Vmph)	125 MPH
armature resistance (Ra)	.019 Ohms
armature inductance (La)	.0058 Henrys
motor toque constant (Kt)	22.6 Lb-Ft/Amp
motor voltage constant (Ke)	3.4 Volts/MPH

accelerating torque to obtain vehicle speed, and engine torque is derived by using the same characteristic curves that are used for the predictive control. In this case, the independent variables are vehicle speed and throttle position while engine torque is the dependent variable. A copy of the predictive control software was used for the vehicle simulation, but the tables were switched around so that the torque would be "predicted" based on the speed and throttle position. A delay was incorporated into the throttle position to simulate the time that it takes for the engine to produce torque after the gas pedal is pressed.

The inertia factor, J, in the vehicle engine model includes the inertia for both the vehicle engine and drive train, and that of the dynamometer rolls and motor. In the field of dynamometers, inertia is usually spoken of in terms of "Wk^2" with units of Lb-Ft^2. In the case of the vehicle model, the term "J" is equal to Wk^2 divided by 308. The inertia of the dynamometer, shafts, and front roll for this installation was equal to 15,625 $Lb\text{-}Ft^2$. The inertia of the vehicle drive train is on the order of 50.0 $Lb\text{-}Ft^2$, giving a total of 15,675 $Lb\text{-}Ft^2$, or "J" is equal to 50.89. An attempt was made to use this figure in the simulation, but the acceleration and deceleration time was too long (three to four minutes) without any inertia compensation.

Inertia compensation in the dynamometer torque reference is meant to help the vehicle accelerate or decelerate the dynamometer rotor and vehicle roll. From the viewpoint of the vehicle, the rolls and dynamometer rotor have no inertia.

In using the appropriate values for inertia and inertia compensation, the torque regulator could not be stabilized. There are two reasons for this. First, the model is oversimplified, especially in regard to the speed feedback and acceleration calculations. Second, the minimum scan time of the DMC for the torque regulator was ten milliseconds, which limited the response time for the current regulators to around 35 radians per second. The current rate regulator is normally set to 250 radians per second, with the outer current regulator set for 60 radians per second.

In order to obtain a workable system for the purpose of testing the predictive control, a compromise was made on the inertia and inertia compensation. The inertia factor "J" was set to 15.0, or 4,620 Lb-Ft², while the inertia compensation was set for 4,000 Lb-Ft². Section 4.2.2 will include more details in regard to inertia, inertia compensation and dynamometer torque regulator stability.

Figure 4.7 details the torque and current regulators for the dynamometer. This is more or less the same regulation scheme shown in figure 3.5 in chapter three. In this case the scaling constants for current and torque feedback (Ki and Ktlc) are assumed to be one. This can be done because the current scaling is taken care of by the armature resistance in the dynamometer

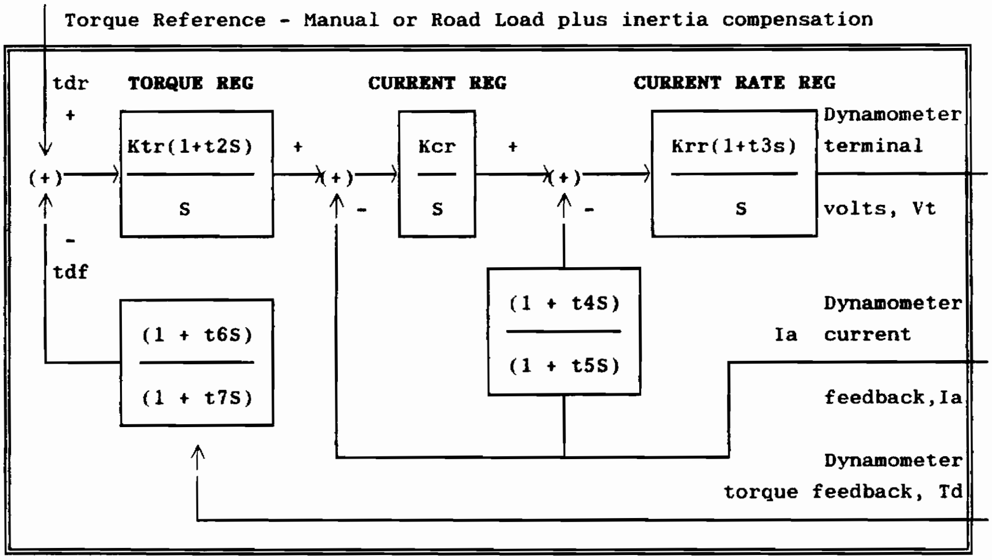


FIGURE 4.7

<u>TEST DYNAMOMETER TORQUE AND CURRENT REGULATOR</u>

model, and the torque scaling is accomplished through the torque constant (Kt) in the dynamometer model.

Inertia compensation and the road load equation are shown in figure 4.8. The road load equation is made up of the top four blocks while the fifth block is the dynamometer inertia compensation. Note that a negative torque reference will cause the engine to produce positive torque. The vehicle will drive the dynamometer, which absorbs the power.

The parameters in figure 4.8 were defined in

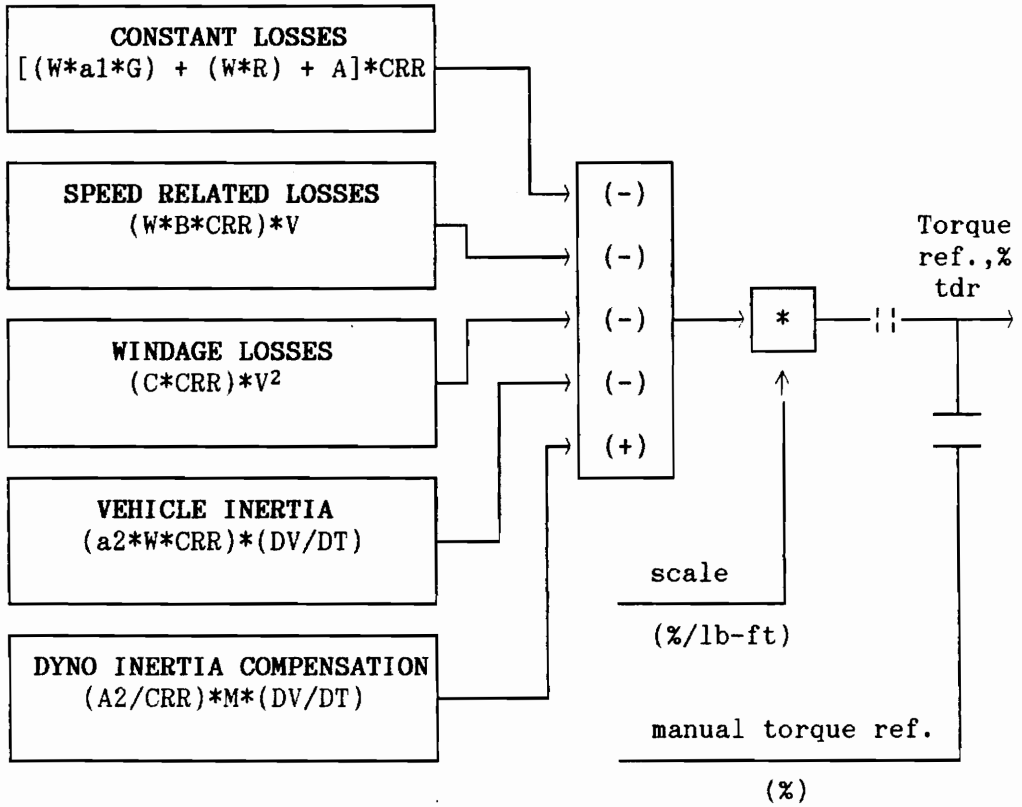


FIGURE 4.8

ROAD LOAD EQUATION & INERTIA COMPENSATION chapter three, section 3.3.1. These parameters, along with the values used for the simulation, are shown in table 4.3.

TABLE 4.3

ROAD LOAD AND INERTIA COMPENSATION PARAMETERS

W - vehicle weight = 2500 Lbs
a1 - Grade coefficient = 1.0
G - Surface grade = 0.0 %
R - rolling resistance = .001
A - Parasitic losses = 3.0 Lbs
CRR - Roll radius = 2.25 Feet
B - Friction loss = .001 Lb/Lb/MPH
C - Vehicle windage = .02 Lb/MPH^2
a2 - Inertia coefficient = .0455 Sec/MPH
M - Dynamometer roll inertia = 4000 Lb-Ft^2

In an actual test cell, the dynamometer compensation would include friction and windage (as described in chapter three). However, the software simulation did not require any friction or windage compensation because none of these losses were included in the dynamometer model.

This completes the description of the models used for the software simulation test. The next section describes the test results using this system.

4.2.2 SIMULATION TEST RESULTS

In order to perform the required tests for the predictive control, it was necessary to first tune the dynamometer regulators and the throttle speed regulator. Table 4.4 shows the final parameter values for the dynamometer regulators.

TABLE 4.4

TORQUE AND CURRENT REGULATOR PARAMETERS

TORQUE REGULATOR	CURRENT REGULATORS
Ktr = 8.0	Kcr = 25
	Krr = 3.5
t2 = .1 seconds	t3 = .07 seconds
t6 = .1 seconds	t4 = .125 seconds
t7 = .2 seconds	t5 = .1 seconds

Due to the fact that the dynamometer current regulators were simulated in a DMC with a ten millisecond scan rate, it was only possible to obtain a response of 50 radians per second for the inner current loop. The outer current loop response was set around 30 radians per second, and the torque regulator was fixed at ten. The slow inner current regulator caused problems. Figure 4.9 shows instabilities in the torque feedback when the vehicle speed is changing. The higher the rate of change, the worse the instabilities were.

The fluctuating torque feedback is due to the changing CEMF caused by the changing vehicle speed. The inner current regulator is just not fast enough to correct for the changing CEMF. However, the average torque around the fluctuations is equal to the reference.

In figure 4.9 the throttle controller is regulating the speed of the vehicle. A speed reference change from ten to 35 percent caused the increase in speed feedback, and also resulted in the changing torque since inertia compensation is included in the dynamometer torque reference. Note that the torque goes all the way to plus ten percent (the dynamometer is producing power) in order to help accelerate the rolls. This demonstrates why the torque feedback cannot be used directly for the predictive control. If it were used, the predictive control would calculate a zero throttle position when an increase in speed is being requested. This is why the torque reference before the inertia compensation is used for the predictive control.

With the above facts in mind, the instabilities in the torque feedback do not make any difference for testing the predictive control. For this reason, the tuning of the dynamometer regulators were not changed.

The throttle control speed regulator was easier to tune than the dynamometer regulators. The final

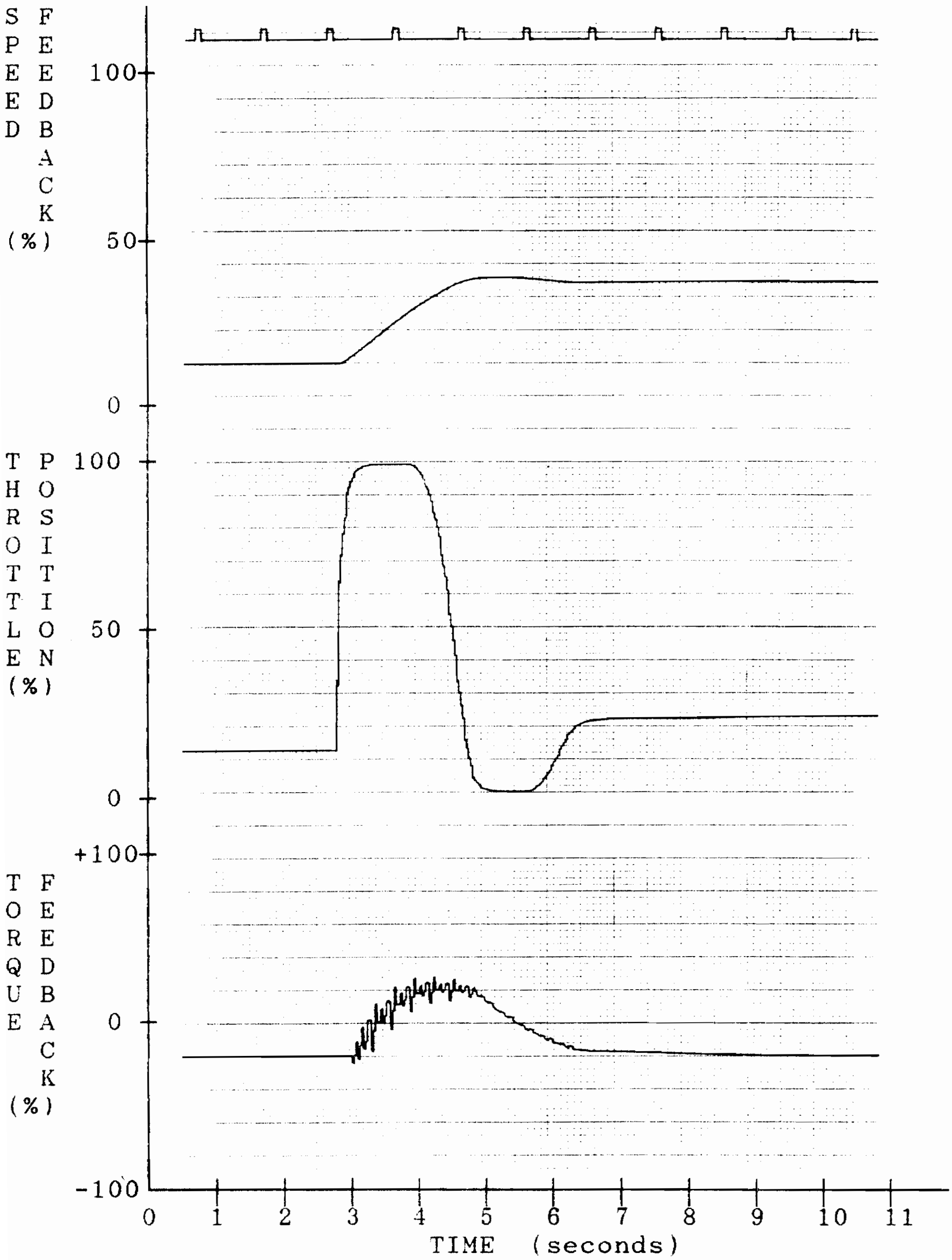


FIGURE 4.9

TORQUE FEEDBACK WITH INERTIA COMPENSATION speed regulator tuning parameters are shown below in table 4.5.

TABLE 4.5

THROTTLE SPEED REGULATOR PARAMETERS

Integrator gain, Ki = 35.0
Integrator lead, ta = .5 seconds
Feedback lead, tc = .19 seconds
Feedback lag, td = .1 seconds
Position lag, tb = .1 seconds

It was possible to demonstrate the interaction between the dynamometer torque regulator and the throttle speed regulator. In order to do this, it was necessary to reduce the amount of inertia, J, in the vehicle model from fifteen 15 (4620 Lb-Ft^2) to 4.5 (1386 Lb-Ft^2). Inertia compensation was not included in the torque reference. The first trace of figure 4.10 shows the effect of having the response time of the two regulator systems too close together. Note that the instability is speed related. As the speed is reduced to 50 percent, the regulation is very stable. The second set of traces show the effect of reducing the speed regulator gain (Ki) until there was no interaction. In this case there is no speed or torque instabilities when the same speed of 80 percent is reached. (Just as a matter of interest, note that the speed and throttle response are a lot different in figure 4.10 than they

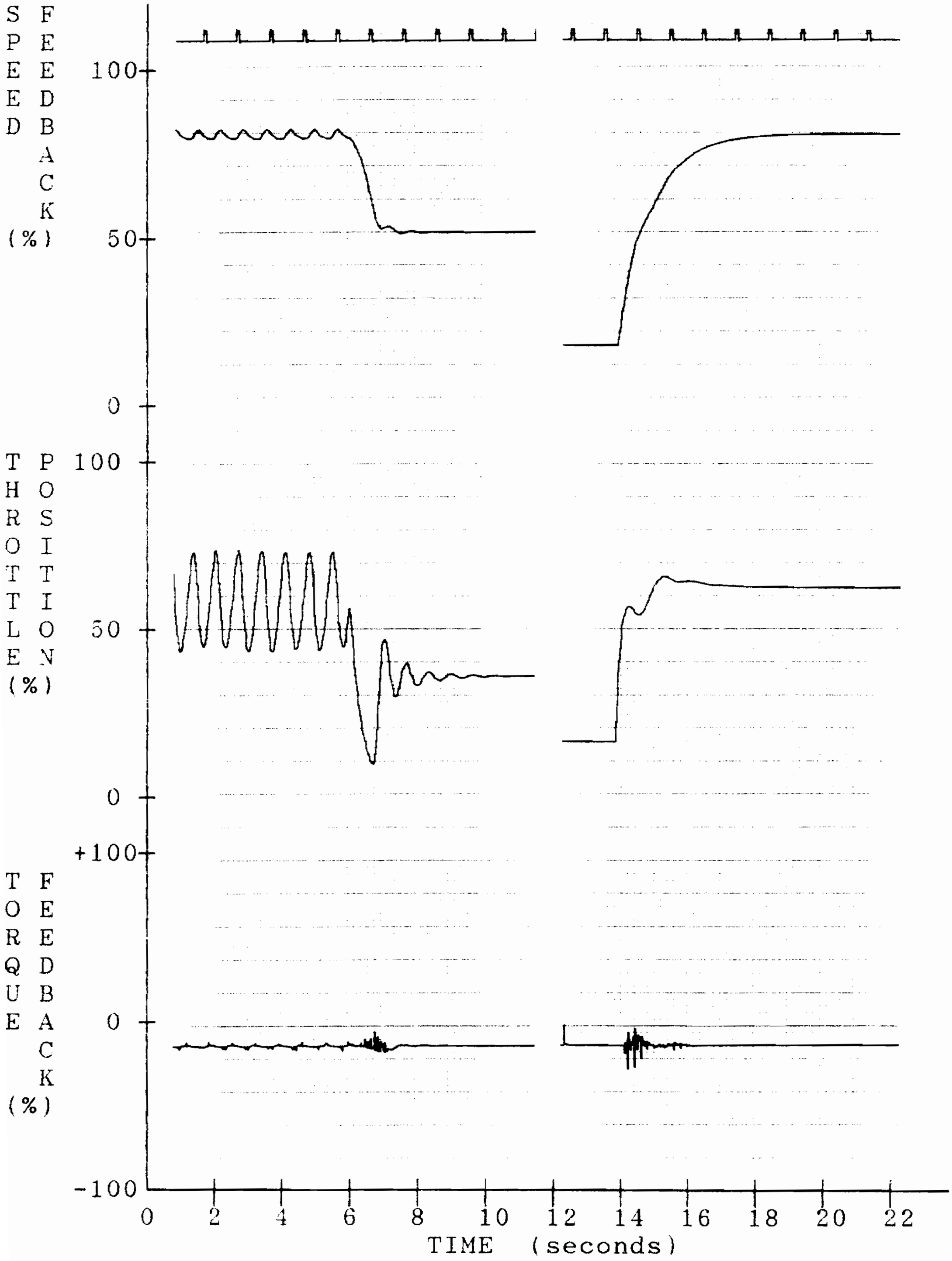


FIGURE 4.10

SPEED - TORQUE REGULATOR INTERACTION

are in figure 4.9. This is due to the reduced inertia in the engine model. With this smaller inertia, the vehicle can accelerate a lot faster.)

The rest of the testing was performed with the regulators set up as shown in table 4.4 and 4.5 in this section, and as shown in table 4.2 and 4.3 in section 4.2.1. Engine inertia, J, was set at fifteen.

The speed regulator was tuned with the torque fixed at twenty percent, and the vehicle speed between fifteen and seventeen percent. This point was used for tune up because it is in the range of the highest speed to throttle position ratio. A small change in throttle position will result in a large change in speed. The response to small speed reference changes is shown by the first trace in figure 4.11. The second trace show the response to a larger change in speed reference with the torque fixed at 25 percent. Note that the time scale is different between the two traces. The response for both traces is nearly critically damped - there is no overshoot. However, as will be shown in tests for the predictive control, the speed regulator response does change its characteristics with different operating points. It should be noted that the speed response and throttle action are very similar between the on site test (as shown in figure 4.2) and the simulation tests shown in figure 4.11. They are not exactly the same,

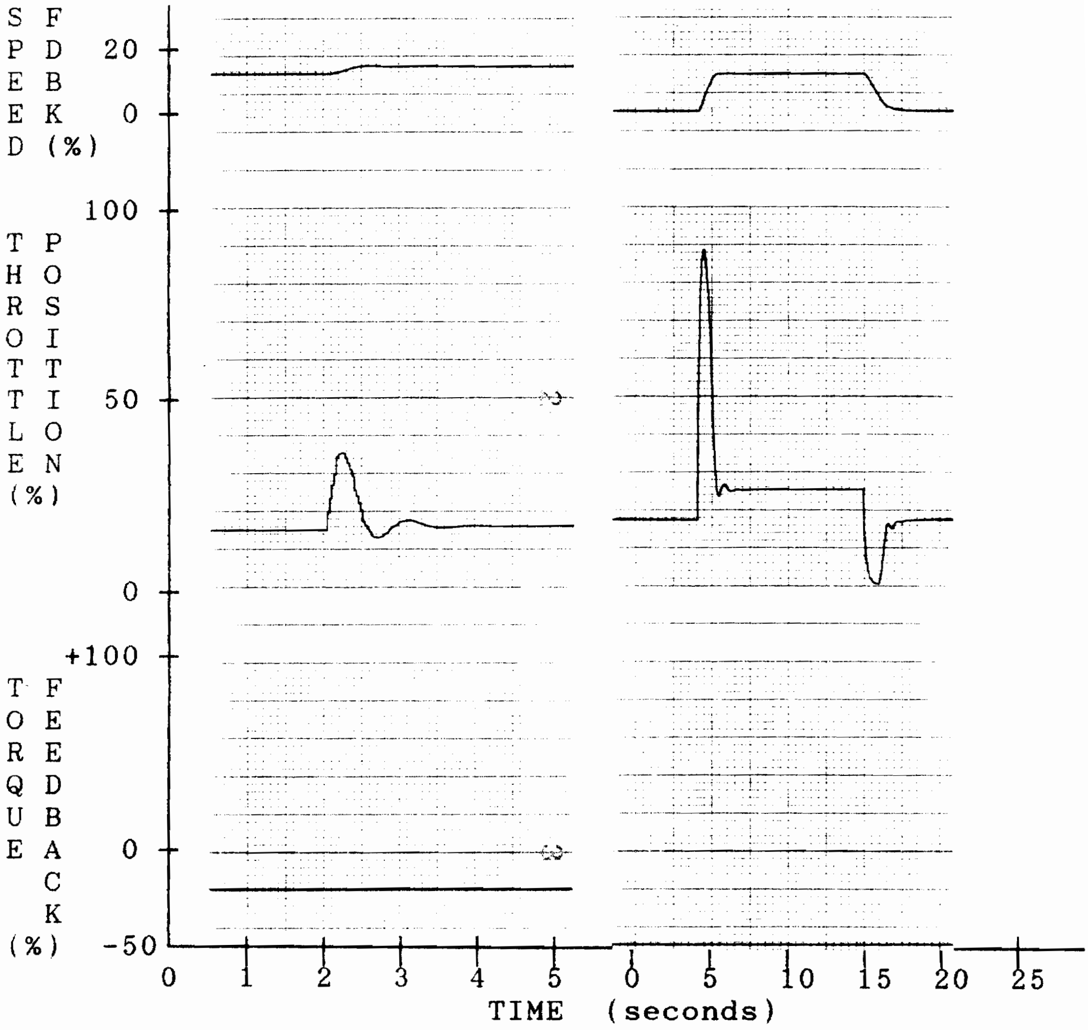


FIGURE 4.11

SIMULATION SPEED REGULATOR RESPONSE

but close enough to allow for confidence in the simulation code and setup.

Results of the predictive control tests using the software simulation show that the system will work under all operating conditions, and that it will improve the response of the speed regulator. Figure 4.12 shows

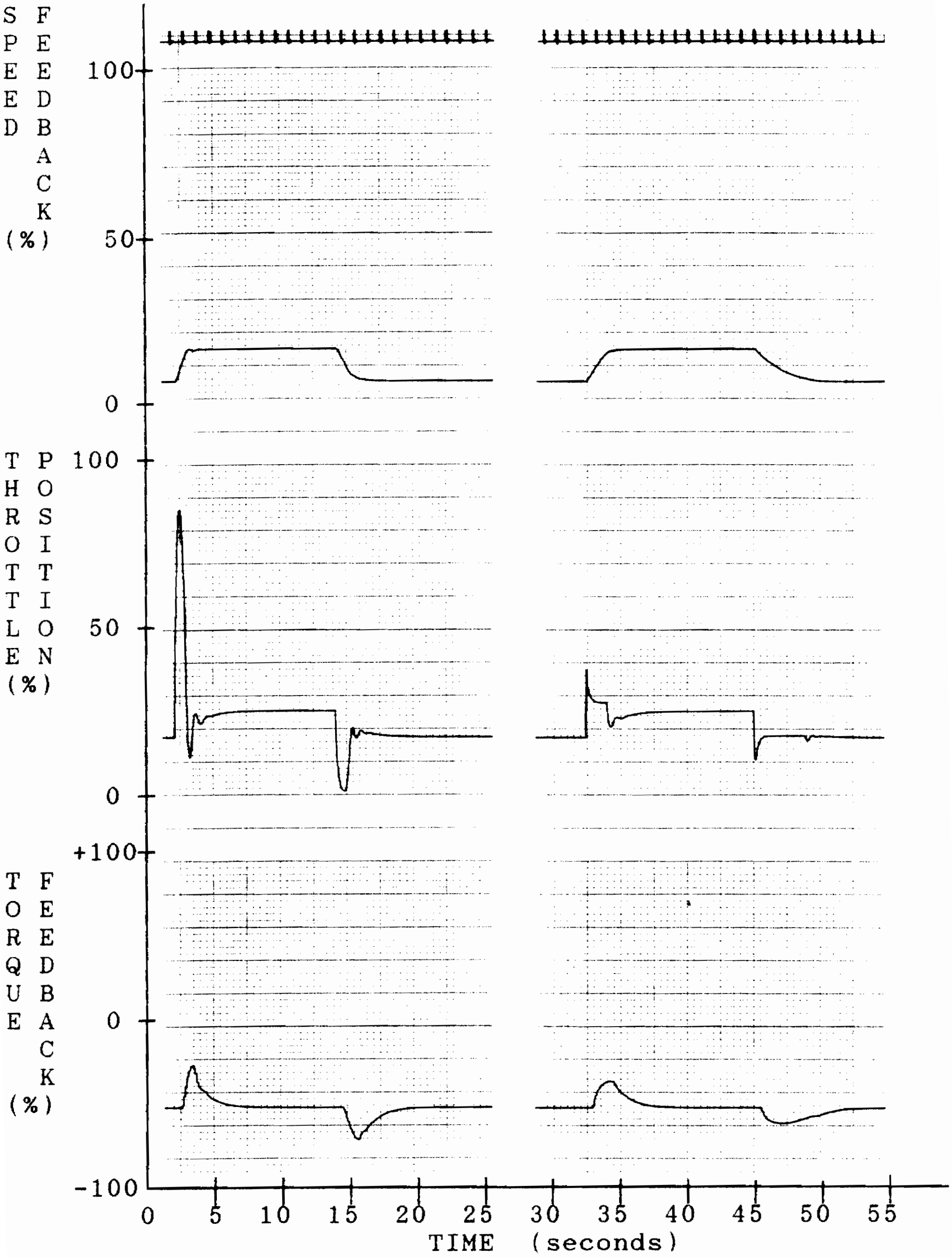


FIGURE 4.12

PREDICTIVE CONTROL TEST WITH INERTIA COMPENSATION the results of one of the tests. The first trace shows the speed response without the predictive control. The predictive control is enabled for the second trace. The torque was fixed at 50 percent, but inertia compensation was included in the torque reference. The effects of inertia compensation can be seen by the changes in torque reference when the vehicle speed is changing. The torque reference does indicate that the faster the rate of change of vehicle speed, the higher the inertia compensation will be.

The response of the pure speed regulator in the first trace shows a little over and under shoot. This disappears when the predictive control is enabled. The points where the predictive control is enabled and disabled can be seen by studying the second trace of figure 4.12 (the enable - disable points were set for one and two percent speed respectively). The predictive control is enabled just about at 32.5 seconds, when the throttle is nearly 40 percent. The throttle goes to its predicted point of 28 percent based on the torque reference of 50 percent (inertia compensation is not included). At 34 seconds, the predictive control is disabled because the speed feedback is within two percent of the speed reference. At this point the speed regulator cuts back in and brings the speed to exactly fifteen percent as requested. The same sequence of events takes place on deceleration to five percent speed.

The most important test was to find how the predictive control worked with the road load equation. In this case the torque reference to the predictive control would be changing based on absolute speed and the rate of change of the vehicle speed. Figure 4.13 shows the response of just the speed regulator to a step change from twenty to 40 percent (and then to 30 percent) in the speed reference. Figure 4.14 shows the response with the predictive control enabled.

The time to reach the requested speed is longer when the predictive control is enabled, but there is no overshoot when the speed feedback is close to the new reference. By studying this figure and others in this section, it can be seen that the speed response is a lot more consistent with the predictive control than without it.

By inspecting the torque reference and throttle position in figure 4.14, the effect of the road load equation on the predicted throttle position can be seen. Between three and 13.5 seconds, the predicted throttle position rises from 33 to 40 percent, and then slowly falls to 26 percent when the speed regulator cuts back in. The changing throttle position is due to the torque required to accelerate the vehicle from twenty to 40 percent speed. Increases in speed related torque are

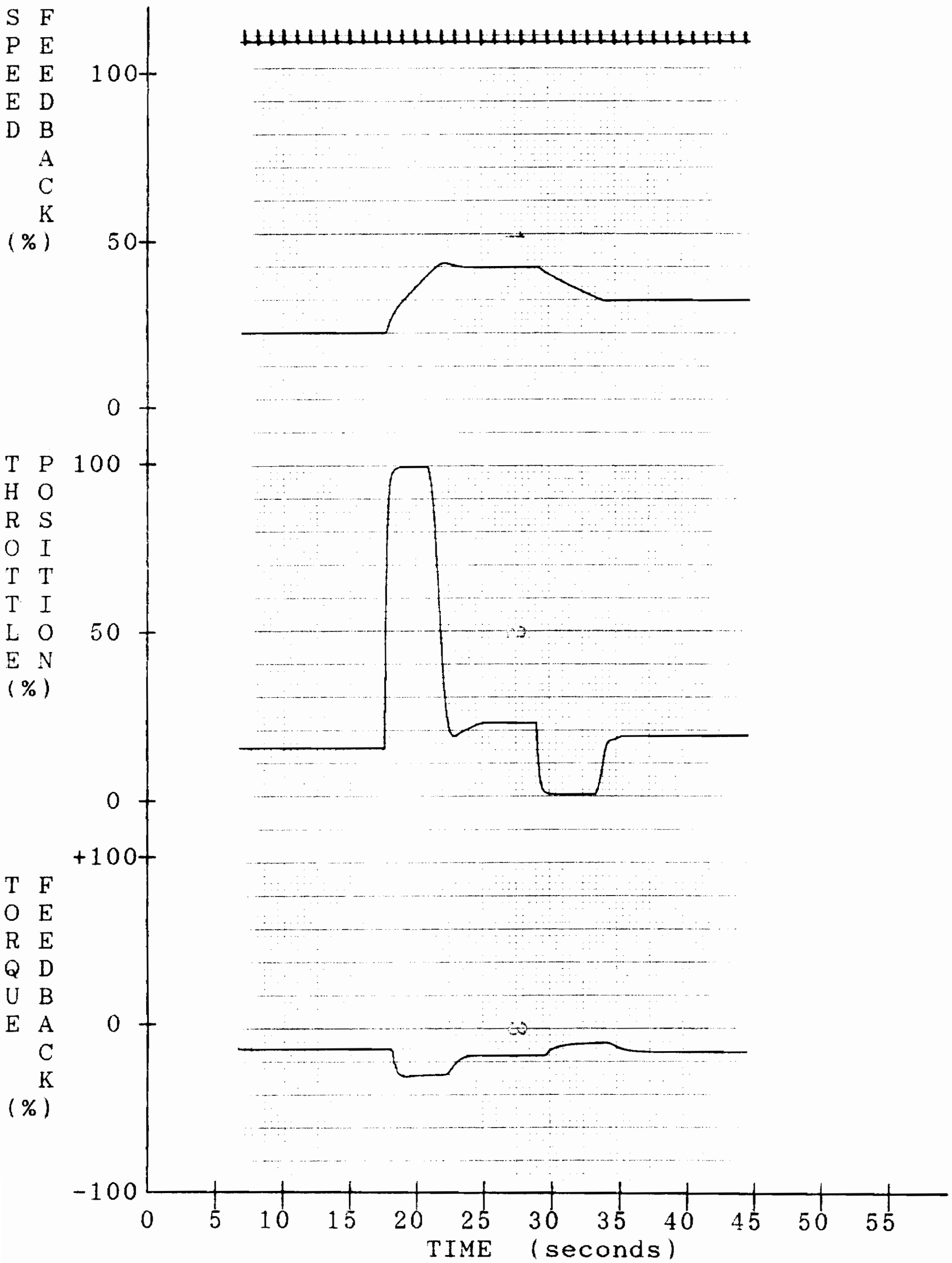


FIGURE 4.13

SPEED RESPONSE WITH OUT PREDICTIVE CONTROL

- ROAD LOAD EQUATION USED -

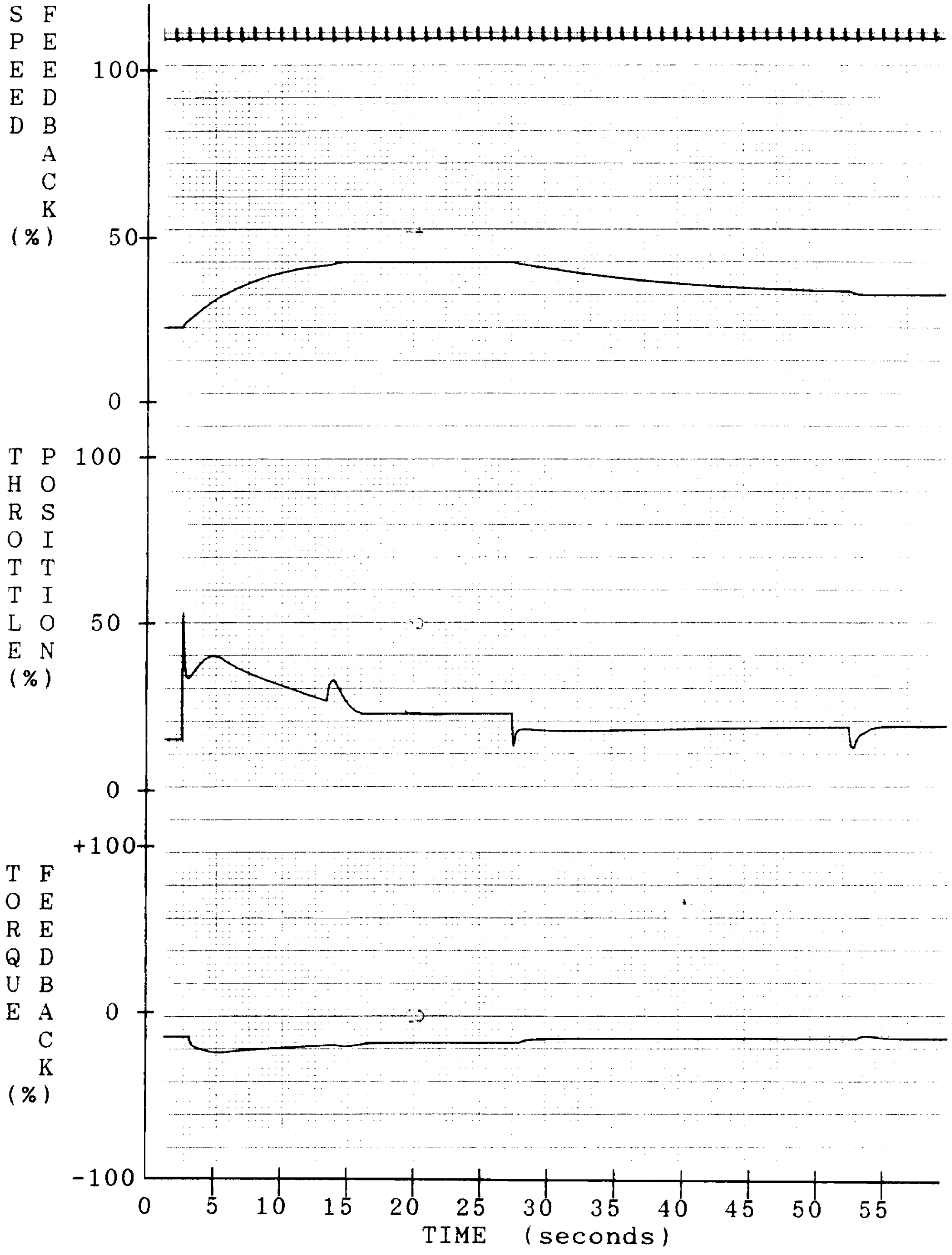


FIGURE 4.14

SPEED RESPONSE WITH PREDICTIVE CONTROL

- ROAD LOAD EQUATION USED -

also effecting the throttle position. With the road load equation, the predicted throttle position will always be higher during acceleration (and lower for deceleration) than required at steady state speed. As the actual speed approaches the speed reference point, the acceleration rate becomes smaller. This causes the predicted throttle position to go down, which further reduces the acceleration rate. With this action, the speed of the vehicle moves smoothly to the desired speed, giving a consistent speed response.

The higher predicted throttle position also means that the engine characteristic map for the predictive control does not have to exactly match the real vehicle characteristics. It just needs to be close so that when the speed regulator takes over, there is not too large of a change in throttle position.

Appendix C includes more strip chart recordings which show the operation of the predictive control at various operating conditions. In all cases, the response using only the speed regulator is included. The beginning of appendix C includes a summary of the strip chart recordings that are included in the appendix.

This completes chapter four, system testing on site and via simulation. Chapter five contains a discussion of the results, recommendations for improvements, and the summary.

CHAPTER 5

DISCUSSION AND SUMMARY

Chapter five is divided into three sections. The first is a discussion of the test results, both on site testing and simulation testing. Included in this section are recommendations for improvements to the predictive control and solutions to some of the problems encountered.

The second section covers a discussion of the two major problems encountered during on site testing, and possible solutions. The first problem has to do with the stepping motor missing pulses during high acceleration and torque conditions. The second problem has to do with resetting the idle and full throttle positions to the same points when the engine map procedure was performed.

Finally, the third section is a summary of the project.

5.1 Test results and improvements

The simulation test results show that the predictive control does work, and that it does improve the speed response of the vehicle. A comparison of the on site test results and those using the simulation software show that the simulation code is fairly accurate. Compare figure 4.5 in section 4.1.2 (page 99) to figure C-2 on page C-4 in appendix C. The speed response in both cases is very similar. In both cases, the target speed was reached in about fifteen seconds for a change in speed of ten percent. However, the throttle action is different between the two. The initial throttle action can be explained by the point at which the predictive control is supposed to cut in. For the on site test, the predictive control cuts in when the speed error is greater than seven percent. For the simulation, the point was set for two percent. The difference in the final throttle action is the result of different regulator setup and differences in the actual vehicle and the vehicle model. As stated in chapter four, the inertia for the simulation does not reflect the actual situation. However, the fact that the vehicle response time is nearly the same between the on site test and the simulation indicate that the simulation is close.

With the above facts in mind, the results from the simulation test can be used with some confidence to predict how well the actual system will perform.

Both the on site tests and the simulation tests show an improvement in the speed response to changes in the speed reference. This is especially true at the point in time when the actual speed is approaching the target speed. With only the speed regulator active, there is overshoot, undershoot, or a good response depending on the operating conditions. When the predictive control is enabled the response is very close to being critically damped, no matter what the operating conditions. This point of consistency in response is one of the more important characteristics of the predictive control regulating system.

One difference between the pure speed regulator and the predictive control that is obvious from the results in chapter four is the time for the vehicle speed to reach its target. With the dynamometer running with a fixed torque reference the time to reach the target speed is a lot longer with the predictive control than with the speed regulator. This is because the predictive control puts the throttle to the point it needs to be for the target speed. The speed regulator puts the throttle to 100 percent until the speed feedback is close to the target. Thus the faster time to the reference. This is especially obvious when inspecting figure 4.4 from section 4.2.2 on page 98 (on site test results). The time to target for the speed regulator was about four seconds. With the predictive control, the time was on the order of fourteen seconds.

Under most testing situations at the Ford wind tunnel, this is not a problem. As a matter of fact, the Ford Company lead technician who was overseeing the work during test stated that for most tests, they did not care how long it took for the vehicle to reach its new speed. The biggest concern was a consistent response from test to test, and a high degree of accuracy under steady state conditions.

For any case where this would be a problem, there are several possible solutions. First of all, it should be noted that this is not a problem when the dynamometer torque reference is controlled by the road load equation. This is because during acceleration (or deceleration) the torque reference includes the torque required to accelerate (or decelerate) the vehicle. This will result in a throttle position that is higher (or lower) than that required at the target steady state speed. This action is obvious by studying figure C-13 in appendix C. In this case the throttle position was predicted to be over 100 percent because of the large accelerating torque from the road load equation.

If the dynamometer is running with a fixed torque reference, one solution to the problem would be to force the throttle to a point higher than the predicted point until the speed feedback was close to the reference. At this point, the throttle would go back to the predicted point until the feedback was even closer to the reference, at which time the speed regulator would cut back in. The amount of "over prediction" could be dependent on the difference between the target and the actual feedback. This would give a response which is similar to the response when the road load equation is used. During deceleration, the case would be just the opposite. The control would use "under prediction" so that the throttle would be set to a point less than that normally predicted.

Another solution would be to simulate the required accelerating torque in the throttle control DMC. This would have the same effect as having the road load equation (at least the vehicle acceleration part) in the throttle DMC. This would not effect the torque reference, just the predicted throttle position. This function would only be used when the dynamometer is regulating torque with a fixed reference.

This brings up another point which became obvious during the on site tests at the Ford wind tunnel. It was not possible to set the full and idle throttle positions to exactly the same points that were used during the engine mapping test. As a result, there were some predicted throttle points that were less than what was actually required. The result was that when the predictive control was enabled, the speed never got close to the required reference. This is not only an issue for throttle calibration, but also general accuracy and resolution of the engine map.

Throttle calibration and engine map accuracy was not a problem with the simulation since the vehicle model characteristics were the same as the engine map for the predictive control. However, this cannot be done in a real situation. The engine map will never exactly match the real vehicle characteristics.

An exact match between the engine map and actual vehicle characteristics is not necessarily a problem when the road load equation is being used, but it could be under other modes of operation. The solution to this potential problem is the same as that for the slow time to target. Either simulate an acceleration torque requirement, or use a variable "over prediction" factor based on the difference between the speed feedback and the reference. Another idea would be to add a fixed offset to the predicted throttle position. The sign of the offset would depend on whether the vehicle is accelerating or decelerating. This offset would be present all the time, but the speed regulator would still cut in when the feedback was close (one to two percent) to the reference. The offset could be made operator adjustable to allow for varying degrees of accuracy or throttle calibration.

A number of the figures for predictive control response show either a fast start just before the predictive control cuts in or a fast finish when the speed regulator cuts back in. In both cases this is due to the high gain of the speed regulator. Both before and after the predictive control is active, there is enough speed error to cause a large throttle action by the speed regulator. One solution to this is to reduce the amount of error required for the predictive control to cut in, and for the speed regulator to cut back in after the predictive control. The simulation had these error points set at two and one percent respectively. For the on site tests, the error bands were set for seven and five percent respectively. Another solution would be to modify the speed regulator tuning parameters when the predictive control is active, and leave them active for a set amount of time after the speed regulator cuts back in. After the set time delay, the high speed regulator tuning parameters would be switched back in so that steady state speed would be held within the accuracy requirements. This would tend to soften the response just before steady state speed is attained.

Before moving on to the next section, it should be noted that interaction between the dynamometer torque regulator and the throttle control speed regulator was not really a problem. This was true for both the on site tests and the simulation tests. It was possible to show the interaction with the simulation, but only by reducing the amount of inertia in the engine model. This problem could show up in the actual wind tunnel if the inertia compensation for the dynamometer is tuned properly. This would have the effect of reducing the inertia seen by the engine to a very small value.

As far as the simulation code went, the dynamometer regulators and the dynamometer itself did not have the power and speed necessary to use the proper values for inertia and inertia compensation. As stated in chapter four, a compromise had to be made on the amount of inertia and inertia compensation in order to obtain a working system. The main reason being the limited scan time of the DMC. The secondary reason was that the model of the dynamometer system was quite simple in comparison to the actual system.

The most important factors for inertia compensation is for the dynamometer system to have a high rate of controlled current and voltage change, and to be able to produce enough current in order to accelerate or decelerate the motor at the proper rates. In any case, the interaction can be tuned out by reducing the throttle speed regulator response, as shown by the simulation tests.

The next section will briefly discuss a few of the problems encountered in the on site tests and possible solutions.

5.2 On site problems and solutions

The most difficult problem that was encountered during the on site testing involved the indexer and stepping motor. During times of high acceleration of the stepping motor, the motor would miss pulses if the torque was too high. However, the problem was really with the controlling indexer. If the motor could not obtain the requested position fast enough, the indexer would assume a stall condition and reset the absolute zero position so that the feedback would match the reference. Because of this problem the actual position feedback from the pulse tachometer would be less than the requested reference. A reference of 100 percent throttle position would result in an actual position of only 90 percent. A reference of zero percent would result in an actual position of minus ten percent.

General Electrics' application engineering group specified the indexer and stepping motor system because of its low cost, and the high torque characteristics. However, the indexer is normally applied to positioning systems for the machine tool industry. The indexer control method was not designed to be part of a fast regulating system like that of the throttle speed control. It was a real challenge to design hardware and software that allowed this system to be used in the method that was required.

The real solution to this problem would be to use a different indexer and stepping motor system - one that has a more applicable positioning control method.

However, there are methods to solve the problem using the present indexer. One such solution would be a combination of reducing the acceleration rate and increasing the gearing between the motor and the throttle movement. An increase in the gearing would reduce the torque requirements and increase the resolution between the idle and full throttle positions. A decrease in the acceleration rate would also reduce the torque requirements. This solution has the one drawback of reducing the positioning response time which introduces a higher lag constant in the speed regulator. Reduction of the acceleration rate is the solution used to get around the problem during the on site tests.

A more sophisticated solution would be to keep the high acceleration rates and perform software recalibration of the throttle position on the fly. The throttle DMC always knows the exact throttle position from the pulse tachometer. During control of the throttle position, the software would continuously check the actual feedback against the reference. When the feedback starts to become less than the reference due to missed indexer pulses, the software would add an offset to the position reference sent to the indexer. The offset would be equal to the error detected. For instance, if a reference of 55 percent is requested, but a feedback of only 54 percent is detected, the DMC would add one percent, sending the indexer a position of 56 percent. The feedback would then be 55 percent as requested from the regulator (or operator during position mode). However, these corrections could only be made during steady state conditions since there is a certain amount of lag between the reference and feedback when the throttle position is moving at a fast rate.

This solution is really a method to get around a basic problem with the control method of the indexer itself. As stated before, the best solution would be to use a system that did not have this problem in the first place.

The other major problem encountered involved resetting the throttle full and idle positions to exactly the same points that were used during the engine map procedure. This is an important consideration because one of the features of this system is the ability to store engine characteristic data and reuse it for similar vehicles.

The easiest solution would be to do away with the feature of reusable engine characteristic data. This would require an engine map procedure be run before any test that would use the predictive control. This is not necessarily a bad idea, since the engine map procedure is fully automated and would take only fifteen to twenty minutes to run. (Of course, the engine map procedure would have to be modified to accept engine RPM as one of the checks for aborting to the next step. This needs to be done in any case.)

If it were required to keep the feature of reusable engine characteristic data, then there are several methods of solving the throttle calibration problem. One such method would be to bypass the acceleration pedal and tie the throttle controller directly to the throttle linkage in the vehicle. This would allow for a more consistent setting of the throttle positions because the slop in the gas pedal would be bypassed. This may not be an acceptable solution since it would require more modification and time to set up a vehicle for testing. Another solution would be to base the full and idle throttle positions on the engine characteristic data itself. The throttle calibration would be performed in the following manner: First, set the full and idle throttle positions in the normal manner. Second, operate the dynamometer in speed mode, and the throttle control in position mode. Third, choose two speed and throttle position points which give a good range of operation, and record (or store) the torque at these points. With known torque and speed, the engine characteristic data would predict what the throttle should be. Finally, recalibrate the throttle position based on the "predicted" positions. Several pairs of points could be selected, and an average throttle calibration based on these points could be used. This calibration technique could be done manually or it could be automated with some extensive software.

Due to slight differences between vehicles of the same model, the calibration will never exactly match that of the original characteristic data. This will not be a problem if the predictive control techniques discussed in section 5.1 are implemented.

With properly applied equipment and good engineering for both the hardware and software, an excellent throttle control system can be built for regulating a vehicles' speed in a test system. The last section of chapter five is the summary of this project.

5.3 Summary

The Ford wind tunnel and environmental test cell is used to simulate actual vehicle operation. The main purpose of the system is to perform long term tests in order to determine how the vehicle and its subsystems hold up to prolonged operation in various environmental conditions. A dynamometer controls the torque of the vehicle while a throttle control system regulates the vehicle speed.

Historically, there have been several problems associated with regulating the speed of the vehicle through the throttle. The main problem has been obtaining consistent and repeatable speed responses to changes in the vehicle torque or reference changes. Related to this is maintaining a high degree of steady state accuracy for the speed regulation. Sometimes, interaction between the torque regulator and the throttle speed regulator can cause instabilities in both systems.

The throttle control system the author designed is an attempt to improve the performance of vehicle speed regulation for a vehicle test system. The idea is to use vehicle characteristic data to predict where the throttle needs to be when there is a new speed reference or disturbances in the torque. The vehicle characteristic data is a three dimensional map of the torque, speed, and throttle position, collected over the operating range of the vehicle.

The dynamometer is powered by a six pulse solid state power converter, with an analog torque regulator. The torque reference is from the master control DMC (Distributed Micro Controller), an Intel 8086 based micro computer. The torque reference can either be fixed or based on a road load equation, which simulates actual operating and road conditions. Inertia compensation for the dynamometer and rolls is included in the torque reference.

The vehicles' throttle position is controlled using a stepping motor and position controlling indexer. The speed is controlled via a digital regulator using another DMC. The predictive control is incorporated in the same DMC. When the speed error becomes greater than a preset limit, the predictive control 'takes over from the speed regulator and places the throttle to the required point based on the speed and torque references. Once the speed feedback is close to the reference again, the speed regulator takes back control and keeps the speed equal to the reference.

The throttle control system was tested both on site at the Ford wind tunnel and by using simulation software. Test results indicated a definite improvement in the speed response when the predictive control was used. The most noticeable improvement involved the point where the speed of the vehicle was just reaching the target speed. In using only the speed regulator, the response varied between undershoot, critically damped, to overshoot depending on the speed and torque levels of operation. With the predictive control enabled, the response was consistent regardless of the operating conditions.

Several problems became apparent during the testing. One problem was that the time for the vehicle to reach the target speed is longer with the predictive control than with a straight speed regulator. This is because the speed regulator places the throttle to 100 percent travel when an increase in speed is requested, whereas the predictive control puts the throttle to the position required for the requested speed (usually less than 100 percent). This problem can be solved by either using the road load equation for controlling the torque or incorporating an accelerating torque requirement in the predicted throttle position.

Overall, the predictive control performed as expected, and improved the system performance over a straight speed regulation system.

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APPENDIX A

Description of Software Documentation

A sample of the documentation of the software for the throttle control DMC is shown in appendix B. The sample includes portions of the predictive control function. The purpose of appendix B is to show how the software is documented, not to give complete details on how the function was implemented.

The first sheet is a title sheet, and is used as instructions to the Linker as to the type of segment, the scan time required, and various other options. The following sheets show the code on a block by block (or logic rung) basis. Above each block is a comment section which describes the function of a group of blocks, or just the next block alone. Associated with each block is a input or output parameter or logical and the mnemonic assigned to the parameters. Below each block is a list of the mnemonics with their associated address and a cross reference showing where that mnemonic is used. The cross reference is based on segment number and block number. For instance, the cross reference "04:0030" refers to segment four, block 30. Below the cross reference section is a listing of all the mnemonics used in the block, with their addresses, and a description of the signals. The origin of the listing of the mnemonics is the variable definition file used by the Linker. On the right hand side of the page for each block is the source code for each block. This is what appears on the CRT screen for the local editor used for the DMC. The code can be modified online by the editor.

Note that the addresses shown in the documentation also indicate the data type. For instance, in the address of ".V0588R", the "V" means the data type is a variable (as opposed to a constant) and the "R" means that this is a real number (floating point).

APPENDIX B

An example of the Software Documentation

"The predictive control segment"

```
..NAME:  PREDICT
..AUTHOR: DR_SOCKY
..COPYRIGHT:  COPYRIGHT        (C)  1987
              BY GENERAL ELECTRIC COMPANY,    U.S.A
..KEYWORDS:
              DMC,SEGMENT
..ABSTRACT: PREDICTIVE_CTRL_REG
.....DESCRIPTION:

.....DEPENDENCIES:
.....MEMORY_SIZE:
..BUILD_INSTRUCTIONS:
.....PROCESSOR:  DMC_EDIT_R3
.....SEGMENT NAME .................................. : PREDICT
.....SEGMENT TYPE (RUN, INTERRUPT, INITIALIZE) ...... : RUN
.....SEGMENT INTERRUPT NUMBER ....................... :
.....SEGMENT SCHEDULING RATE, AND UNIT .............. : 50 MS
.....8087 CO-PROCESSOR USED (YES / NO) .............. : YES
.....SEGMENT STACK SIZE (# OF BYTES) ................ :
.....SYMBOLIC NAME SPLIT CHAR (DEFAULT HYPHEN) ...... :
.....USE LOGIC ACCELERATOR ON SEGMENT ? (Y/N) ....... : N
```

```
  ***********************************************************************
  ***********************************************************************
  ********      LOGIC   CONTROL   FOR   PREDICTOR               *********
  ********                                                      *********
  ***********************************************************************
  ***********************************************************************
  CHECK TO SEE IF ENGINE MAP DATA IN TABLE ONE IS VALID
  =====================================================

  THIS IS USED AS A PERMISSIVE FOR RUNNING PREDICTIVE CONTROL
  "IN USE" VARIABLE FOR TABLE 1, ITEM 8 ("EMP1_U"):
       0.0 -----> ENGINE MAP DATA NOT VALID
       1.0 -----> ENGINE MAP DATA VALID
ANY OTHER NUMBER INDICATES NONE VALID DATA


             +-----------------------------------------------------+
             !             ACMPOO  -- ANALOG COMPARE               !B# 0020
             !              X = COMPARISON OF A TO B               !
             !               _______________________               !
             !               !     COMPARE         !               !
  EMP1_U     !(P-0) A        !CODE!    A TO B      !       X (LO-1)!EMVALD
 ------------!-------------->! - -!- - - - - - - - !->-------------!------------
             !               !  0 !      =         !               !
             !               !  1 !     < >        !               !
             !               !  2 !      <         !               !
  1.0        !(P-1) B        !  3 !      >         !               !
  -----------!-------------->!  4 !      >=        !               !
             !               !  5 !      <=        !               !
             !               +---------------------+               !
  0          !(P-2) CODE                                           !
 ------------!-----------------+                                   !
             !                                                     !
             !                                                     !
  TRUE       !(LI-1)                                               !
 ------------!---------------------> ENABLE                        !
             +-----------------------------------------------------+

  EMVALD------.L0130    04:0030

  NAME        ADDRESS   VALUE    DEVTYP LOCATION PAGE#   DESCRIPTION
  ----        -------   -----    ------ -------- -----   -----------
  EMP1_U-------.V0588R                                   TBL 1,ITEM 8 - ENGINE MAP DATA GOOD
  EMVALD------.L0130                                     PR CTRL - ENGINE MAP DATA IS VALID (IN USE)
```

```
LD  TRUE---------.L0001
BLK ACMPOO
B#  0020
P-0 EMP1_U-------.V0588R
P-1 1.0----------.C18EER
P-2 0------------.C18F2C
STO EMVALD------.L0130
B#  0020
```

```
************************************************************************************************************************
*                    *               *   COPYRIGHT (C) 1988,  BY    *  SYSTEM:FORD_THROTTLE                               *
* DATE:03/18/88      *  REQUISITION  *   GENERAL ELECTRIC COMPANY   *                                                     *
* AUTHOR :DR_SOCKY   *  541-DJ-43789 *   DRIVE SYSTEMS DEPARTMENT   *******************************************************
*                    *  D.S.D        *   SALEM, VA     USA          *  DRAWING : 23788030                                 *
*                    *  S&P_DRIVES_T *                              *  NEXT PAGE: 0063                    PAGE: 0062     *
************************************************************************************************************************
```

```
                                                                                                        ====================  ========
                                                                                                        SEGMENT:04/BLOCK:0020  PG: 0062
                                                                                                        ====================  ========

  ***********************************************************************
  ***********************************************************************
  ********      LOGIC   CONTROL   FOR   PREDICTOR              *********
  ********                                                     *********
  ***********************************************************************
  ***********************************************************************
  CHECK TO SEE IF ENGINE MAP DATA IN TABLE ONE IS VALID
  =====================================================

  THIS IS USED AS A PERMISSIVE FOR RUNNING PREDICTIVE CONTROL
  "IN USE" VARIABLE FOR TABLE 1, ITEM 8 ("EMP1_U"):
       0.0 -----> ENGINE MAP DATA NOT VALID
       1.0 -----> ENGINE MAP DATA VALID
ANY OTHER NUMBER INDICATES NONE VALID DATA

             +-----------------------------------------------------+
             !             ACMPOO  -- ANALOG COMPARE               !B# 0020
             !              X = COMPARISON OF A TO B               !
             !               _______________________               !
             !               !     COMPARE         !               !
  EMP1_U     !(P-0) A        !CODE!    A TO B      !       X (LO-1)!EMVALD
-------------!-------------->! - -!- - - - - - - - !->-------------!------------
             !               !  0 !       =        !               !
             !               !  1 !      < >       !               !
             !               !  2 !       <        !               !
  1.0        !(P-1) B        !  3 !       >        !               !
  -----------!-------------->!  4 !       >=       !               !
             !               !  5 !       <=       !               !
             !               +---------------------+               !
  0          !(P-2) CODE      ^                                    !
-------------!-----------------+                                   !
             !                                                     !
             !                                                     !
  TRUE       !(LI-1)                                               !
-------------!--------------------> ENABLE                         !
             +-----------------------------------------------------+

  EMVALD------.L0130    04:0030

  NAME        ADDRESS    VALUE    DEVTYP LOCATION PAGE#   DESCRIPTION
  ----        -------    -----    ------ -------- -----   -----------
  EMP1_U------.V0588R                                     TBL 1,ITEM 8 - ENGINE MAP DATA GOOD
  EMVALD------.L0130                                      PR CTRL - ENGINE MAP DATA IS VALID (IN USE)

************************************************************************************************************************
*                    *                *   COPYRIGHT (C) 1988,  BY     *  SYSTEM:FORD_THROTTLE                              *
* DATE:03/18/88      *  REQUISITION   *   GENERAL ELECTRIC COMPANY    *                                                    *
* AUTHOR :DR_SOCKY   *  541-DJ-43789  *   DRIVE SYSTEMS DEPARTMENT    ******************************************************
*                    *  D.S.D         *   SALEM, VA     USA           *  DRAWING : 237B8030                                *
*                    *  S&P_DRIVES_T  *                               *  NEXT PAGE: 0063                     PAGE: 0062    *
************************************************************************************************************************
```

```
LD  TRUE--------.L0001
BLK ACMPOO
B#  0020
P-0 EMP1_U------.V0588R
P-1 1.0---------.C18EER
P-2 0-----------.C18F2C
STO EMVALD------.L0130
B#  0020
```

```
                                                                                                ===================  ========
                                                                                                SEGMENT:04/BLOCK:0020  PG: 0062
                                                                                                ===================  ========
  ***********************************************************************
  ***********************************************************************
  ********      LOGIC   CONTROL   FOR   PREDICTOR                *********
  ********                                                       *********
  ***********************************************************************
  ***********************************************************************
  CHECK TO SEE IF ENGINE MAP DATA IN TABLE ONE IS VALID
  =====================================================

  THIS IS USED AS A PERMISSIVE FOR RUNNING PREDICTIVE CONTROL
  "IN USE" VARIABLE FOR TABLE 1, ITEM 8 ("EMP1_U"):
       0.0 -----> ENGINE MAP DATA NOT VALID
       1.0 -----> ENGINE MAP DATA VALID
ANY OTHER NUMBER INDICATES NONE VALID DATA

             +------------------------------------------------------+
             !             ACMPOO  -- ANALOG COMPARE                !B# 0020
             !              X = COMPARISON OF A TO B                !
             !                ________________________              !
             !                !     COMPARE          !              !
  EMP1_U     !(P-0) A         !CODE!    A TO B       !       X (LO-1)!EMVALD
 ------------!--------------->! - -!- - - - - - - -  !->------------!------------
             !                !  0 !       =         !              !
             !                !  1 !      < >        !              !
             !                !  2 !       <         !              !
  1.0        !(P-1) B         !  3 !       >         !              !
 ------------!--------------->!  4 !       >=        !              !
             !                !  5 !       <=        !              !
             !                +----------------------+              !
  0          !(P-2) CODE        ^                                   !
 ------------!------------------+                                   !
             !                                                      !
             !                                                      !
  TRUE       !(LI-1)                                                !
 ------------!---------------------> ENABLE                         !
             +------------------------------------------------------+

  EMVALD------.L0130    04:0030

  NAME         ADDRESS   VALUE    DEVTYP LOCATION PAGE#   DESCRIPTION
  ----         -------   -----    ------ -------- -----   -----------
  EMP1_U------.V0588R                                     TBL 1,ITEM 8 - ENGINE MAP DATA GOOD
  EMVALD------.L0130                                      PR CTRL - ENGINE MAP DATA IS VALID (IN USE)
```

```
LD  TRUE--------.L0001
BLK ACMPOO
B#  0020
P-0 EMP1_U------.V0588R
P-1 1.0---------.C18EER
P-2 0-----------.C18F2C
STO EMVALD------.L0130
B#  0020
```

```
 ************************************************************************************************************************
 *                    *               *   COPYRIGHT (C) 1988,  BY   *  SYSTEM:FORD_THROTTLE                                *
 * DATE:03/18/88      *  REQUISITION  *   GENERAL ELECTRIC COMPANY  *                                                      *
 * AUTHOR :DR_SOCKY   *  541-DJ-43789 *   DRIVE SYSTEMS DEPARTMENT  ********************************************************
 *                    *  D.S.D        *   SALEM, VA    USA          *  DRAWING : 237B8030                                  *
 *                    *  S&P_DRIVES_T *                             *  NEXT PAGE: 0063                      PAGE: 0062     *
 ************************************************************************************************************************
```

```
                                                                                                 ===================  ========
                                                                                                 SEGMENT:04/BLOCK:0030  PG: 0063
                                                                                                 ===================  ========
PREDICTIVE CONTROL IS READY
===========================
PERMISSIVES FOR PREDICTIVE CONTROL TO START

1) THROTTLE CONTROL MUST BE ON
2) MUST BE IN SPEED MODE
3) COMMUNICATIONS WITH MASTER CONTROL IS OK
4) IF IN AUTO MODE, COMMUNICATIONS WITH VAX IS OK
5) NOT INHIBIT PREDICTIVE CONTROL FROM VAX AND NOT INHIBIT PREDICTIVE CONTROL FORM OP STN
6) MUST BE A VALID ENGINE MAP FOR "IN USE" TABLE.
                                                                                                        LD  T_ON---------.L0088
 T_ON    MCSMPBB MCCMOK  VXCMOK  NOPCPBA NOPCPBB EMVALD                  PCRDY                          AN  MCSMPBB------.G09201
+--] [--+--] [--+--] [--+--] [--+--]/[--+--]/[--+--] [--+--------+--------+--(   )-                     AN  MCCMOK-------.L006A
    *              *      !    *          !      !    *                   !                             LD  VXCMOK-------.L0066
                          !               !      !                        !                             ANF NOPCPBA------.GFD201
                          !               !      !                        !                             OR  TMANURB------.G09207
                          !TMANURB        !TAUTORB!                       !PCOACKC                      ANS
                          +--] [--+--------+--] [--+                      +--(   )-                     LDF NOPCPBB------.G09210
                                                                                                        OR  TAUTORB------.G09206
                                                                                                        ANS
                                                                                                        AN  EMVALD-------.L0130
                                                                                                        STO PCRDY--------.L0131
                                                                                                        B#  0030
                                                                                                        STO PCOACKC------.G05256
                                                                                                        B#  0030
T_ON---------.L0088    02:0100    03:0480    03:0490    05:0910,   ETC
MCSMPBB------.G09201   08:0480    08:0490    08:0500    08:0510    08:0550
MCCMOK-------.L006A   *08:0110    08:0150    08:0210    08:0480    08:0490
VXCMOK-------.L0066   *08:0060    08:0150    08:0240    09:0010    10:0840
TMANURB------.G09207   08:0130    08:0540    10:0020    10:0120    10:0190
TAUTORB------.G09206   08:0130    08:0140    08:0160    08:0540    10:0020
EMVALD-------.L0130   *04:0020
PCRDY--------.L0131    04:0050    04:0060    04:0070    04:0080    04:0090

NAME         ADDRESS   VALUE    DEVTYP LOCATION PAGE#   DESCRIPTION
----         -------   -----    ------ -------- -----   -----------
T_ON---------.L0088                                     THROTTLE CONTROLLER IS ON W/ A MODE
MCSMPBB------.G09201                                    MC-SPEED MODE REQUEST
MCCMOK-------.L006A                                     CMMM - MASTER CONTROL COMMUNICATIONS IS OK
VXCMOK-------.L0066                                     COMM - MICRO VAX COMMUNICATIONS IS OK
NOPCPBA------.GFD201                                    INHIBIT PREDICTIVE CONTROL REQUEST (THROTTLE)
TMANURB------.G09207                                    THROTTLE MANUAL MODE REQUEST
NOPCPBB------.G09210                                    INHIBIT PREDICTIVE CONTROL REQUEST (MC)
TAUTORB------.G09206                                    THROTTLE AUTO MODE REQUEST
EMVALD-------.L0130                                     PR CTRL - ENGINE MAP DATA IS VALID (IN USE)
PCRDY--------.L0131                                     PR CTRL - PREDICTIVE CONTROL READY (PERM)
PCOACKC------.G05256                                    PREDICTIVE CONTROL IS ACTIVE (THROTTLE)
***********************************************************************************************************************
* .                  *                  *  COPYRIGHT (C) 1988,  BY      *  SYSTEM:FORD_THROTTLE                           *
* DATE:03/18/88      *  REQUISITION     *  GENERAL ELECTRIC COMPANY     *                                                  *
* AUTHOR DR_SOCKY    *  541-DJ-43789    *  DRIVE SYSTEMS DEPARTMENT     ***************************************************
*                    *  D.S.D           *  SALEM, VA     USA            *  DRAWING : 237B8030                              *
*                    *  S&P_DRIVES_T    *                               *  NEXT PAGE: 0064                   PAGE: 0063    *
***********************************************************************************************************************
```

```
                                                                                                =====================  ========
                                                                                                SEGMENT:04/BLOCK:0050  PG: 0064
                                                                                                =====================  ========

+++++++++++++++++++++++++++++++++++++++++++++++++++
+++++++++++++++++++++++++++++++++++++++++++++++++++
+++++++++  CHECK ERROR        BETWEEN SPEED REF AND
+++++++++  SPEED FEEDBACK (TURN PRED CNTRL ON OR OFF)
+++++++++++++++++++++++++++++++++++++++++++++++++++
+++++++++++++++++++++++++++++++++++++++++++++++++++
ABSOLUTE THE SPEED ERROR SIGNAL FROM THE SPEED REGULATOR

                                                                                                         LD  PCRDY-------.L0131
           +-----------------------------------------------------+                                       BLK AABS00
           !             AABS00  -- ANALOG ABSOLUTE VALUE        !B# 0050                                B#  0050
           !                                                     !                                       P-0 SPERR1------.V028AR
           !                       X = !A!                       !                                       P-1 PCSERR------.V03A6R
           !                                                     !
           !                       __________                    !
           !                      ! ABSOLUTE!                    !
           !                      !  VALUE  !                    !
SPERR1     !(P-0) A               ! !     ! !             X (P-1)!PCSERR
-----------!--------------------->! !  A  ! !->------------------!-------------
           !                      ! !     ! !                    !
           !                      !_________!                    !
           !                                                     !
           !                                                     !
           !                                                     !
           !                                                     !
           !                                                     !
           !                                                     !
PCRDY      !(LI-1)                                         (LO-1)!
-----------!---------------------> ENABLE >----------------------!-------------
           +-----------------------------------------------------+

PCRDY-------.L0131   *04:0030   04:0060    04:0070    04:0080    04:0090
SPERR1------.V028AR  *05:0910   05:0920    05:0930    09:0730
PCSERR------.V03A6R   04:0060   04:0070

NAME        ADDRESS   VALUE    DEVTYP LOCATION PAGE#   DESCRIPTION
----        -------   -----    ------ -------- -----   -----------
PCRDY-------.L0131                                     PR CTRL - PREDICTIVE CONTROL READY (PERM)
SPERR1------.V028AR                                    SPD REG - SPEED ERROR SIGNAL (REF-FBK)
PCSERR------.V03A6R                                    PR CTRL - ABSOLUTED SPEED ERROR


************************************************************************************************************************
*                    *               *   COPYRIGHT (C) 1988,  BY    *  SYSTEM:FORD_THROTTLE                            *
* DATE:03/18/88      *  REQUISITION  *   GENERAL ELECTRIC COMPANY   *                                                  *
* AUTHOR :DR_SOCKY   *  541-DJ-43789 *   DRIVE SYSTEMS DEPARTMENT   ****************************************************
*                    *  D.S.D        *   SALEM, VA    USA           *  DRAWING : 237B8030                              *
*                    *  S&P_DRIVES_T *                              *  NEXT PAGE: 0065                   PAGE: 0064    *
************************************************************************************************************************
```

COMPARE SPEED ERROR TO A CONSTANT.
IF GREATER THAN CONSTANT THEN ENABLE PREDICTIVE CONTROL.

THIS WILL PICK UP "PREDICTIVE CONTROL START", WHICH WILL THEN CAUSE
THE SPEED REGULATOR TO SWITCH OUT, AND THE PREDICTIVE CONTROL TO
GIVE THROTTLE POSITION COMMANDS.

```
LD  PCRDY--------.L0131
BLK ACMPOO
B#  0060
P-0 PCSERR-------.V03A6R
P-1 KPCEBL-------.C02F6R
P-2 3------------.C18F4C
STO PCENBL-------.L0132
B#  0060
```

```
           +-----------------------------------------------------+
           !             ACMPOO -- ANALOG COMPARE                !B# 0060
           !              X = COMPARISON OF A TO B               !
           !               _______________________               !
           !               !     COMPARE         !               !
PCSERR     !(P-0) A        !CODE!    A TO B      !       X (LO-1)!PCENBL
-----------!-------------->! - -!- - - - - - - - !->-------------!------------
           !               !  0 !      =         !               !
           !               !  1 !     < >        !               !
           !               !  2 !      <         !               !
KPCEBL     !(P-1) B        !  3 !      >         !               !
-----------!-------------->!  4 !      >=        !               !
           !               !  5 !      <=        !               !
           !               +---------------------+               !
3          !(P-2) CODE       ^                                   !
-----------!-----------------+                                   !
           !                                                     !
           !                                                     !
PCRDY      !(LI-1)                                               !
-----------!---------------------> ENABLE                        !
           +-----------------------------------------------------+

PCRDY--------.L0131   *04:0030   04:0050   04:0070   04:0080   04:0090
PCSERR-------.V03A6R  *04:0050   04:0070
PCENBL-------.L0132    04:0110

NAME         ADDRESS   VALUE    DEVTYP LOCATION PAGE#   DESCRIPTION
----         -------   -----    ------ -------- -----   -----------
PCRDY--------.L0131                                     PR CTRL - PREDICTIVE CONTROL READY (PERM)
PCSERR-------.V03A6R                                    PR CTRL - ABSOLUTED SPEED ERROR
KPCEBL-------.C02F6R   7.0                              PR CTRL - SPEED ERROR POINT ENABLE CTRL C.
PCENBL-------.L0132                                     PR CTRL - SPD ERROR > C., ENABLE P CTRL
```

```
COMPARE SPEED ERROR TO A CONSTANT.
IF LESS THEN CONSTANT THAN DISABLE PREDICTIVE CONTROL.

THIS WILL CAUSE THE "PREDICTIVE CONTROL START" BIT TO DROP OUT, AND
THEN THE SPEED REGULATOR WILL TAKE BACK CONTROL OF GIVING THROTTLE
POSITION COMMANDS.
```

```
LD  PCRDY--------.L0131
BLK ACMP00
B#  0070
P-0 PCSERR-------.V03A6R
P-1 KPCDBL-------.C02FAR
P-2 2------------.C18E4C
STO PCDABL-------.L0133
B#  0070
```

```
           +-----------------------------------------------------+
           !             ACMP00  -- ANALOG COMPARE               !B# 0070
           !              X = COMPARISON OF A TO B               !
           !               ________________________              !
           !               !     COMPARE         !               !
PCSERR     !(P-0) A        !CODE!    A TO B      !       X (LO-1)!PCDABL
-----------!-------------->! - -!- - - - - - - - !->-------------!------------
           !               !  0 !      =         !               !
           !               !  1 !     < >        !               !
           !               !  2 !      <         !               !
KPCDBL     !(P-1) B        !  3 !      >         !               !
-----------!-------------->! 4  !      >=        !               !
           !               !  5 !      <=        !               !
           !               +---------------------+               !
2          !(P-2) CODE       -                                   !
-----------!-----------------+                                   !
           !                                                     !
           !                                                     !
PCRDY      !(LI-1)                                               !
-----------!---------------------> ENABLE                        !
           +-----------------------------------------------------+

PCRDY--------.L0131   *04:0030   04:0050    04:0060    04:0080    04:0090
PCSERR-------.V03A6R  *04:0050   04:0060
PCDABL-------.L0133    04:0120   04:0160

NAME         ADDRESS    VALUE    DEVTYP LOCATION PAGE#   DESCRIPTION
----         -------    -----    ------ -------- -----   -----------
PCRDY--------.L0131                                      PR CTRL - PREDICTIVE CONTROL READY (PERM)
PCSERR-------.V03A6R                                     PR CTRL - ABSOLUTED SPEED ERROR
KPCDBL-------.C02FAR    5.0                              PR CTRL - SPEED ERROR POINT DISABLE CTRL C.
PCDABL-------.L0133                                      PR CTRL - SPD ERROR < C., DISABLE P CTRL
```

```
CHECK TO SEE IF SPEED REFERENCE IS WITHIN LIMITS OF GEARING FOR THIS TEST.
==========================================================================

CHECK TO SEE IF REF GREATER THAN LOWER LIMIT.


           +-----------------------------------------------------+
           !             ACMPOO  -- ANALOG COMPARE               !B# 0080
           !              X = COMPARISON OF A TO B               !
           !                                                     !
           !               _______________________               !
           !               !     COMPARE         !               !
VSREF      !(P-0) A        !CODE!    A TO B      !       X (LO-1)!PCSGTL
-----------!-------------->! - -!- - - - - - - - !->-------------!------------
           !               !  0 !      =         !               !
           !               !  1 !     < >        !               !
           !               !  2 !      <         !               !
EMMNS2     !(P-1) B        !  3 !      >         !               !
-----------!-------------->! 4  !      >=        !               !
           !               !  5 !      <=        !               !
           !               +---------------------+               !
4          !(P-2) CODE       ^                                   !
-----------!-----------------+                                   !
           !                                                     !
           !                                                     !
PCRDY      !(LI-1)                                               !
-----------!---------------------> ENABLE                        !
           +-----------------------------------------------------+

PCRDY--------.L0131   *04:0030   04:0050   04:0060   04:0070   04:0090
VSREF--------.V034ER   04:0090   04:0200   05:0910  *06:0170   06:0180
EMMNS2-------.V0552R  *08:0790   08:0820   12:0300
PCSGTL-------.L013D    04:0110   04:0120

NAME         ADDRESS    VALUE    DEVTYP LOCATION PAGE#   DESCRIPTION
----         --------   -----    ------ -------- -----   -----------
PCRDY--------.L0131                                      PR CTRL - PREDICTIVE CONTROL READY (PERM)
VSREF--------.V034ER                                     SPD REF - VEHICLE SPEED REF-TO REG.
EMMNS2-------.V0552R                                     EMAP - MC SPD REF INTERMEDIATE CALC 2 MIN
PCSGTL-------.L013D                                      PR CTRL - SPD > LOWER LIMIT FOR GEAR
```

```
LD   PCRDY--------.L0131
BLK  ACMPOO
B#   0080
P-0  VSREF--------.V034ER
P-1  EMMNS2-------.V0552R
P-2  4------------.C18F6C
STO  PCSGTL-------.L013D
B#   0080
```

```
************************************************************************************************************
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* DATE:03/18/88        *  REQUISITION  *  GENERAL ELECTRIC COMPANY  *                                      *
* AUTHOR :DR_SOCKY     *  541-DJ-43789 *  DRIVE SYSTEMS DEPARTMENT  ****************************************
*                      *  D.S.D        *  SALEM, VA     USA         *  DRAWING : 23788030                  *
*                      *  S&P_DRIVES_T *                            *  NEXT PAGE: 0068        PAGE: 0067   *
************************************************************************************************************
```

```
CHECK TO SEE IF REF LESS THAN UPPER LIMIT.

           +------------------------------------------------------+
           !             ACMP00  -- ANALOG COMPARE                !B# 0090
           !              X = COMPARISON OF A TO B                !
           !                                                      !
           !                ________________________              !
           !                !      COMPARE          !             !
VSREF      !(P-0) A         !CODE!    A TO B        !     X (LO-1)!PCSLTU
-----------!--------------->! - -!- - - - - - - - - !->-----------!------------
           !                ! 0  !       =          !             !
           !                ! 1  !      < >         !             !
           !                ! 2  !       <          !             !
EMMXS2     !(P-1) B         ! 3  !       >          !             !
-----------!--------------->! 4  !       >=         !             !
           !                ! 5  !       <=         !             !
           !                +-----------------------+             !
5          !(P-2) CODE        ^                                   !
-----------!------------------+                                   !
           !                                                      !
           !                                                      !
PCRDY      !(LI-1)                                                !
-----------!----------------------> ENABLE                        !
           +------------------------------------------------------+
```

```
LD  PCRDY--------.L0131
BLK ACMP00
B#  0090
P-0 VSREF--------.V034ER
P-1 EMMXS2-------.V055AR
P-2 5------------.C18E6C
STO PCSLTU-------.L013E
#  0090
```

```
PCRDY--------.L0131  *04:0030   04:0050    04:0060     04:0070    04:0080
VSREF--------.V034ER  04:0080   04:0200    05:0910    *06:0170    06:0180
EMMXS2-------.V055AR  04:0200   07:0100   *08:0810     08:0820
PCSLTU-------.L013E   04:0110   04:0120

NAME        ADDRESS   VALUE    DEVTYP LOCATION PAGE#   DESCRIPTION
----        -------   -----    ------ -------- -----   -----------
PCRDY--------.L0131                                    PR CTRL - PREDICTIVE CONTROL READY (PERM)
VSREF--------.V034ER                                   SPD REF - VEHICLE SPEED REF-TO REG.
EMMXS2-------.V055AR                                   EMAP - MC SPD REF INTERMEDIATE CALC 2 MAX
PCSLTU-------.L013E                                    PR CTRL - SPD < UPPER LIMIT FOR GEAR
```

```
+++++++++++++++++++++++++++++++++++++++++++++++++++
+++++++++++++++++++++++++++++++++++++++++++++++++++
+++++++++   START PREDICTIVE CONTROL  AND
+++++++++   REGULATOR SWITCHING LOGIC
+++++++++++++++++++++++++++++++++++++++++++++++++++
+++++++++++++++++++++++++++++++++++++++++++++++++++
TRIGGER A ONE SHOT WHEN PREDICTIVE CONTROL IS ENABLED

                                              +-----------------------+
 PCENBL  PCSGTL  PCSLTU                       !            KPLS00     !
+--] [--+--] [--+--] [--+------+-------+------+ENABLE                 !
    *      *       *                          !   INPUT LOGICALS      !
                                              !   FOR NEXT BLOCK      !
                                              !                       !
                                              +-----------------------+
                                                                                                        LD  PCENBL------.L0132
           +------------------------------------------------------+                                     AN  PCSGTL------.L013D
           !            KPLS00  - LOGICAL PULSE                   !B# 0110                              AN  PCSLTU------.L013E
           !                                                      !                                     BLK KPLS00
           !                                                      !                                     B#  0110
           !                                                      !                                     P-O PCTMP1------.L0136
           !                       +--------+                     !                                     STO PCENOS------.L0134
****-ENABLE !(LI-1) ENABLE         ! SINGLE !         OUTPUT (LO) !PCENOS                               B#  0110
------------!-------+-------------->! SHOT  +---------------------!----------
           !       !        ------ !        !   ---               !
           !       !      --       +--------+ --   ----           !
           !       !                          ->!T!<-             !
           !       !                                              !
           !       !                                              !
           !       !                   T = SEGMENT SCAN RATE      !
           !       !                                              !
           !       !                                              !
           !       !                                 OUTPUT (P-O) !PCTMP1
           !       +----------------------------------------------!----------
           !                                                      !
           +------------------------------------------------------+
PCENBL------.L0132   *04:0060
PCSGTL------.L013D   *04:0080   04:0120
PCSLTU------.L013E   *04:0090   04:0120
PCENOS------.L0134    04:0120
NAME        ADDRESS   VALUE    DEVTYP LOCATION PAGE#   DESCRIPTION
----        -------   -----    ------ -------- -----   -----------
PCENBL------.L0132                                     PR CTRL - SPD ERROR > C., ENABLE P CTRL
PCSGTL------.L013D                                     PR CTRL - SPD > LOWER LIMIT FOR GEAR
PCSLTU------.L013E                                     PR CTRL - SPD < UPPER LIMIT FOR GEAR
PCTMP1------.L0136                                     PR CTRL - ONE SHOT TEMP LOGICAL
PCENOS------.L0134                                     PR CTRL - ENABLE PREDICTIVE CTRL ONE SHOT

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* AUTHOR :DR_SOCKY   *  541-DJ-43789 *   DRIVE SYSTEMS DEPARTMENT   ***************************************************
*                    *  D.S.D        *   SALEM, VA    USA           * DRAWING : 237B8030                              *
*                    *  S&P_DRIVES_T *                              * NEXT PAGE: 0070                    PAGE: 0069   *
***********************************************************************************************************************
```

```
                                                                                                ======================  ********
                                                                                                SEGMENT:04/BLOCK:0120  PG: 0070
                                                                                                ======================  ********
START PREDICTIVE CONTROL.
THIS ENABLES THE CALCULATIONS. START AND CALCS DONE WILL CAUSE REGULATOR
TO SWITCH FROM SPEED REGULATOR TO PREDICTIVE CONTROL
                                                                                                         LD  PCENOS------.L0134
 PCENOS                         PCRDY                                   PCSTRT                           LD  PCSTRT------.L0138
+--] [--+-------+-------+-------+--] [--+-------+-------+-------+-------+--(   )-                        ANF PCDABL------.L0133
    *                           !   *                                                                    AN  PCSGTL------.L013D
                                !                                                                        AN  PCSLTU------.L013E
                                !                                                                        ORS
 PCSTRT  PCDABL  PCSGTL  PCSLTU !                                                                        AN  PCRDY-------.L0131
+--] [--+--]/[--+--] [--+--] [--+                                                                        STO PCSTRT------.L0138
    *      *       *       *                                                                             B#  0120
PCENOS------.L0134   *04:0110
PCSTRT------.L0138    04:0130   04:0200    04:0570    04:0580    04:0590
PCDABL------.L0133   *04:0070   04:0160
PCSGTL------.L013D   *04:0080   04:0110
PCSLTU------.L013E   *04:0090   04:0110
PCRDY-------.L0131   *04:0030   04:0050    04:0060    04:0070    04:0080
NAME        ADDRESS   VALUE    DEVTYP LOCATION PAGE#   DESCRIPTION
----        -------   -----    ------ -------- -----   -----------
PCENOS------.L0134                                     PR CTRL - ENABLE PREDICTIVE CTRL ONE SHOT
PCSTRT------.L0138                                     PR CTRL - START AND RUN PREDICTIVE CONTROL
PCDABL------.L0133                                     PR CTRL - SPD ERROR < C., DISABLE P CTRL
PCSGTL------.L013D                                     PR CTRL - SPD > LOWER LIMIT FOR GEAR
PCSLTU------.L013E                                     PR CTRL - SPD < UPPER LIMIT FOR GEAR
PCRDY-------.L0131                                     PR CTRL - PREDICTIVE CONTROL READY (PERM)
                                                                                                ======================  ********
                                                                                                SEGMENT:04/BLOCK:0130  PG: 0066
                                                                                                ======================  ********
COMMAND TO SWITCH IN PREDICTIVE CONTROL AND SWITCH OUT SPEED REGULATOR

THIS WILL PICK UP WHEN THE PREDICTIVE CONTROL CALCULATIONS ARE DONE,
AND SEAL IN UNTIL:
SPEED MODE IS DESELECTED,   OR
DISABLE PREDICTIVE CONTROL ---> HOLD THROTTLE POSITION OUTPUT  ---->
BREAK SEAL ON ABOVE RUNG  ----> SPEED REGULATOR SWITCHED IN   ---->
HOLD RELEASED.
                                                                                                         LD  PCSTRT------.L0138
 PCSTRT  PCCDN          PCRDY                                           SWTOPC                           AN  PCCDN-------.L0139
+--] [--+--] [--+-------+--] [--+-------+-------+-------+-------+-------+--(   )-                        LD  SMSEL-------.L006F
    *      *            !  *                                                                             ANF HOLDIN------.L009F
                        !                                                                                AN  SWTOPC------.L013A
 SMSEL  HOLDIN  SWTOPC  !                                                                                ORS
                        !                                                                                AN  PCRDY-------.L0131
+--] [--+--]/[--+--] [--+                                                                                STO SWTOPC------.L013A
    *      *       *                                                                                     B#  0130
```

```
PCSTRT------.L0138    04:0120  *04:0120    04:0200    04:0570    04:0580
PCCDN-------.L0139   *04:0770
SMSEL-------.L006F    08:0230  *08:0490    09:0230    09:0240    09:0380
HOLDIN------.L009F    05:1450   09:0240    09:0250    09:0300    09:0390
SWTOPC------.L013A    04:0140   09:0500    09:0640
PCRDY-------.L0131   *04:0030   04:0050    04:0060    04:0070    04:0080
NAME        ADDRESS   VALUE    DEVTYP LOCATION PAGE#   DESCRIPTION
----        -------   -----    ------ -------- -----   -----------
PCSTRT------.L0138                                     PR CTRL - START AND RUN PREDICTIVE CONTROL
PCCDN-------.L0139                                     PR CTRL - PREDICTIVE CONTROL CALCS DONE
SMSEL-------.L006F                                     MODECTL - SPEED   MODE SELECTED
HOLDIN------.L009F                                     MODECTL - THROTTLE OUTPUT IN "HOLD"
SWTOPC------.L013A                                     PR CTRL - SWITCH TO PRED. CTRL (TO REG SEG)
PCRDY-------.L0131                                     PR CTRL - PREDICTIVE CONTROL READY (PERM)
                                                                                                 =====================  ========
                                                                                                 SEGMENT:04/BLOCK:0140  PG: 0071
                                                                                                 =====================  ========

PRESET THE REGULATOR WITH THE THROTTLE POSITION FEED BACK.  THIS IS SO
WHEN THE MODE SWITCHES BACK TO SPEED REGULATION, THE TRANSFER WILL
BE BUMPLESS.

THIS BIT GOES TO THE INTEGRATOR IN ORDER TO PRESET.
IT ALSO MOVES THE FEEDBACK TO THE PRESET WORD.

                                                                                                          LD  SWTOPC------.L013A
 SWTOPC  PCMSIN  SMSIN                                                   PCPSRG                           AN  PCMSIN------.L009A
+--] [--+--] [--+--]/[--+-------+-------+-------+-------+-------+-------+--(   )-                         ANF SMSIN-------.L0096
    *       *       *                                                                                     STO PCPSRG------.L013B
                                                                                                          B#  0140

SWTOPC------.L013A    04:0130  *04:0130    09:0500    09:0640
PCMSIN------.L009A    04:0170  *05:1430    05:1560    05:1580    08:0190
SMSIN-------.L0096    04:0170  *05:1400    05:1560    05:1580    06:0110
PCPSRG------.L013B    04:0150   09:0530

NAME        ADDRESS   VALUE    DEVTYP LOCATION PAGE#   DESCRIPTION
----        -------   -----    ------ -------- -----   -----------
SWTOPC------.L013A                                     PR CTRL - SWITCH TO PRED. CTRL (TO REG SEG)
PCMSIN------.L009A                                     MODECTL - PREDICTIVE CONTROL SWITCH IN
SMSIN-------.L0096                                     MODECTL - SPEED MODE SWITCHED IN
PCPSRG------.L013B                                     PR CTRL - PRESET SPD REG INTEGRATOR
```

```
                                                                                                ====================  ========
                                                                                                SEGMENT:04/BLOCK:0150  PG: 0072
                                                                                                ====================  ========
MOVE THE THROTTLE POSITION FEEDBACK TO THE PRESET FOR THE
SPEED REGULATOR INTEGRATOR.

 PCPSRG                                       +-----------------------+                                  LD  PCPSRG-------.L013B
                                              !            XAMVV00    !                                  BLK XAMVV00
+--) [--+-------+-------+-------+------+------+ENABLE                 !                                  B#  0150
    *                                         !     ANALOG MOVE       !                                  P-0 TCPOSFC------.G062CR
                                              !                       !                                  P-1 SRPRST-------.V02A2R
                                              !                       !
                                              !        TCPOSFC SRPRST !
                                              !                       !
                                              !        =0=R=R= =1=R=W=!
                                              !        INPUT   OUTPUT !
                                              !                       !
                                              +-----------------------+
PCPSRG-------.L013B  *04:0140   09:0530
TCPOSFC------.G062CR *05:0630   05:0640    06:0440    07:0030    07:0190
SRPRST-------.V02A2R  05:0940  *09:0080   *09:0180   *09:0400

NAME        ADDRESS   VALUE    DEVTYP LOCATION PAGE#   DESCRIPTION
----        -------   -----    ------ -------- -----   -----------
PCPSRG-------.L013B                                    PR CTRL - PRESET SPD REG INTEGRATOR
TCPOSFC------.G062CR                                   THROTTLE POSITION FEEDBACK TO UVAX    (%)
SRPRST-------.V02A2R                                   SPD REG - SPEED REG INTEGRATOR PRESET VAR.
                                                                                                ====================  ========
                                                                                                SEGMENT:04/BLOCK:0160  PG: 0068
                                                                                                ====================  ========

TRIGGER ONE SHOT WHEN IT IS TIME TO DISABLE THE PREDICTIVE CONTROL.
                                                                                                         LD  PCDABL-------.L0133
           +-------------------------------------------------------+                                     BLK KPLS00
           !            KPLS00  - LOGICAL PULSE                    !B# 0160                              B#  0160
           !                                                       !                                     P-0 PCTMP2-------.L0137
           !                                                       !                                     STO PCDAOS-------.L0135
           !                                                       !                                     B#  0160
           !                       +--------+                      !
PCDABL     !(LI-1) ENABLE          ! SINGLE !          OUTPUT (LO) !PCDAOS
-----------!-------+--------------->! SHOT   +----------------------!----------
           !       !        ------ !        !   ---                !
           !       !      --       +--------+ --   ----            !
           !       !                          ->!T!<-              !
           !       !                                               !
           !       !                   T = SEGMENT SCAN RATE       !
           !       !                                               !
           !       !                                  OUTPUT (P-0) !PCTMP2
           !       +-----------------------------------------------!----------
           !                                                       !
           +-------------------------------------------------------+
```

```
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* AUTHOR :DR_SOCKY   * 541-DJ-43789 *    DRIVE SYSTEMS DEPARTMENT   ****************************************************
*                    * D.S.D        *    SALEM, VA    USA           * DRAWING : 23788030                               *
*                    * S&P_DRIVES_T *                               * NEXT PAGE: 0073                    PAGE: 0072    *
************************************************************************************************************************
```

```
PCDABL-------.L0133  *04:0070   04:0120
PCDAOS-------.L0135   04:0170
NAME        ADDRESS   VALUE    DEVTYP LOCATION PAGE#   DESCRIPTION
----        -------   -----    ------ -------- -----   -----------
PCDABL-------.L0133                                    PR CTRL - SPD ERROR < C., DISABLE P CTRL
PCTMP2-------.L0137                                    PR CTRL - ONE SHOT TEMP LOGICAL
PCDAOS-------.L0135                                    PR CTRL - DISABLE PREDICTIVE CTRL ONE SHOT
                                                                                                ====================  ========
                                                                                                SEGMENT:04/BLOCK:0170  PG: 0073
                                                                                                ====================  ========

HOLD THE REGULATOR OUTPUT WHEN TIME TO DISABLE PREDICTIVE CONTROL.
THIS IS SEALED IN UNTIL:
   1) SPEED REGULATOR SWITCHED BACK IN
   2) PREDICTIVE CONTROL IS SWITCHED OUT
   3) PRESET COMMAND TO SPEED REGULATOR GOES LOW
      IN OTHER WORDS, SPEED REGULATOR READY TO TAKE OVER CONTROL
                                                                                                         LD  PCDAOS-------.L0135
 PCDAOS         PCRDY   PMSELL  TMSELL                                  PCHOLD                           LDF SMSIN--------.L0096
+--] [--+-------+--] [--+--]/[--+--]/[--+-------+-------+-------+-------+--(   )-                        OR  PCMSIN-------.L009A
    *           !   *       *       *                                                                    OR  SMPSIN-------.L00A0
                !                                                                                        AN  PCHOLD-------.L013C
                !                                                                                        ORS
 SMSIN  PCHOLD  !                                                                                        AN  PCRDY--------.L0131
+--]/[--+--] [--+                                                                                        ANF PMSELL-------.L00C9
    *   !   *                                                                                            ANF TMSELL-------.L00D9
        !                                                                                                STO PCHOLD-------.L013C
        !                                                                                                B#  0170
PCMSIN  !
+--] [--+
    *   !
 SMPSIN !
+--] [--+
    *
PCDAOS-------.L0135  *04:0160
SMSIN--------.L0096   04:0140  *05:1400    05:1560    05:1580    06:0110
PCMSIN-------.L009A   04:0140  *05:1430    05:1560    05:1580    08:0190
SMPSIN-------.L00A0   05:0940   09:0410    09:0420   *09:0530
PCHOLD-------.L013C   09:0500   09:0660
PCRDY--------.L0131  *04:0030   04:0050    04:0060    04:0070    04:0080
PMSELL-------.L00C9   09:0220  *09:0220    09:0230
TMSELL-------.L00D9   09:0370  *09:0370    09:0380
NAME        ADDRESS   VALUE    DEVTYP LOCATION PAGE#   DESCRIPTION
----        -------   -----    ------ -------- -----   -----------
PCDAOS-------.L0135                                    PR CTRL - DISABLE PREDICTIVE CTRL ONE SHOT
SMSIN--------.L0096                                    MODECTL - SPEED MODE SWITCHED IN
PCMSIN-------.L009A                                    MODECTL - PREDICTIVE CONTROL SWITCH IN
SMPSIN-------.L00A0                                    MODECTL - SPD REG INT. PRESET ACTIVE
PCHOLD-------.L013C                                    PR CTRL - HOLD THROTTLE POS CMND OUTPUT
PCRDY--------.L0131                                    PR CTRL - PREDICTIVE CONTROL READY (PERM)
PMSELL-------.L00C9                                    M LOG - POSITION MODE SELECTED LATCH
TMSELL-------.L00D9                                    M LOG - TORQUE MODE SELECTED LATCH
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* AUTHOR :DR_SOCKY   *  541-DJ-43789 *  DRIVE SYSTEMS DEPARTMENT    ****************************************************
*                    *  D.S.D        *  SALEM, VA    USA            *  DRAWING : 237B8030                              *
*                    *  S&P_DRIVES_T *                              *  NEXT PAGE: 0074                    PAGE: 0073   *
************************************************************************************************************************
```

```
***********************************************************************
********      PREDICTIVE CONTROL  --  TABLE MANIPULATION      ********
********      AND THROTTLE POSITION CALCULATIONS              ********
***********************************************************************

+++++++++++++++++++++++++++++++++++++++++++++++++++
+++++++++  FIND SPEED REF GEAR RANGE IN PU 0 TO 100
+++++++++++++++++++++++++++++++++++++++++++++++++++
SPEED RANGE MAY BE 20 TO 40 PU FOR GEAR 3.  NEED THIS SCALED AS 0 TO 100 FOR
THESE TABLES. (IF AUTOMATIC THEN GEAR RANGE WOULD BE 0 TO 100: CONVERSION
WOULD RESULT IN 0 TO 100).
USE THE FOLLOWING FORMULA:
                  100
TABLE SPD REF = ---------- * (SPD REF - MAXIMUM) + 100
               MAX - MIN
              !__________!
                   ^
                   +-------- THE INVERSE OF THIS TERM IS FOUND IN "MODECTL"
                             SEGMENT
FIND (SPD REF - MAXIMUM)
                                              +-----------------------+
 PCSTRT                                       !            ASUB00     !
+--] [--+------+-------+--------+-------+-----+ENABLE                 !
    *   !                                     !   INPUT LOGICALS      !
        !                                     !   FOR NEXT BLOCK      !
        !                                     !                       !
 T1STRT !                                     !                       !
+--] [--+                                     !                       !
                                              +-----------------------+

           +-----------------------------------------------------+
           !             ASUB00 -- ANALOG SUBTRACT               !B# 0200
           !                                                     !
           !                    X   = A - B                      !
           !                                                     !
           !                                                     !
           !                     __________                      !
           !                     !         !                     !
VSREF      !(P-0) A              !         !            X (P-1)!PCSRF3
-----------!-------------------->!   ---   !->--------------------!------------
           !                     !         !                     !
           !                     !_________!                     !
           !                         ^                           !
EMMXS2     !(P-2) B                  !                           !
-----------!-------------------------+                           !
           !                                                     !
****-ENABLE !(LI-1)                                        (LO-1)!
-----------!--------------------> ENABLE >-----------------------!------------
           +-----------------------------------------------------+
```

```
LD  PCSTRT------.L0138
OR  T1STRT------.L001D
BLK ASUB00
B#  0200
P-0 VSREF-------.V034ER
P-1 PCSRF3------.V03AAR
P-2 EMMXS2------.V055AR
```

```
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*                    *  S&P_DRIVES_T *                                *  NEXT PAGE: 0075                    PAGE: 0074   *
*************************************************************************************************************************
```

```
  PCSTRT------.L0138      04:0120  *04:0120    04:0130    04:0570    04:0580
  T1STRT------.L001D      05:0320   05:0480    05:0630    05:1080    05:1090
  VSREF-------.V034ER     04:0080   04:0090    05:0910   *06:0170    06:0180
  PCSRF3------.V03AAR     04:0210
  EMMXS2------.V055AR     04:0090   07:0100   *08:0810    08:0820
  NAME        ADDRESS     VALUE    DEVTYP LOCATION PAGE#   DESCRIPTION
  ----        -------     -----    ------ -------- -----   -----------
  PCSTRT------.L0138                                       PR CTRL - START AND RUN PREDICTIVE CONTROL
  T1STRT------.L001D                                       ENG TST-START TEST BIT
  VSREF-------.V034ER                                      SPD REF - VEHICLE SPEED REF-TO REG.
  PCSRF3------.V03AAR                                      PR CTRL - SPD REF CALC FOR GEAR IN SPD 3
  EMMXS2------.V055AR                                      EMAP - MC SPD REF INTERMEDIATE CALC 2 MAX
                                                                                                  =====================  ========
                                                                                                  SEGMENT:04/BLOCK:0210  PG: 0075
                                                                                                  =====================  ========

           100
FIND    ------------ * (SPD REF - MAXIMUM)
        MAX - MIN
                                                                                                           BLK ADVD00
             +-----------------------------------------------------+                                       B#  0210
             !             ADVD00  -- ANALOG DIVIDE                !B# 0210                                P-0 PCSRF3------.V03AAR
             !                                                     !                                       P-1 PCSRF4------.V03AER
             !                       X = A / B                     !                                       P-2 EMSRF2------.V0542R
             !                                                     !
             !                                                     !
             !                       ___________                   !
             !                       !         !                   !
  PCSRF3     !(P-0) A                !    o    !            X (P-1)!PCSRF4
  -----------!---------------------->!  ---    !->-----------------!------------
             !                       !    o    !                   !
             !                       !_________!                   !
             !                            ^                        !
             !                            !                        !
  EMSRF2     !(P-2) B                     !                        !
  -----------!----------------------------+                        !
             !                                                     !
             !                                                     !
             !                                                     !
  . .........!(LI-1)                                         (LO-1)!
  -----------!---------------------> ENABLE >----------------------!------------
             +-----------------------------------------------------+

  PCSRF3------.V03AAR   *04:0200
  PCSRF4------.V03AER    04:0220
  EMSRF2------.V0542R    07:0110   *08:0830    12:0290

  NAME        ADDRESS     VALUE    DEVTYP LOCATION PAGE#   DESCRIPTION
  ----        -------     -----    ------ -------- -----   -----------
  PCSRF3------.V03AAR                                      PR CTRL - SPD REF CALC FOR GEAR IN SPD 3
  PCSRF4------.V03AER                                      PR CTRL - SPD REF CALC FOR GEAR IN SPD 4
  EMSRF2------.V0542R                                      EMAP - MC SPD REF INTERMEDIATE CALC 2

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 *                    *  S&P_DRIVES_T *                              *  NEXT PAGE: 0076                  PAGE: 0075      *
 *************************************************************************************************************************
```

```
FIND FINAL SPEED REFERENCE FOR PREDICTIVE CONTROL SCALED 0 TO 100

                  100
PC SPD REF  =  ------------ * (SPD REF - MAXIMUM) + 100
               MAX  -  MIN
                                                                                                         BLK AADDOO

           +-----------------------------------------------------+                                       B#  0220
           !               AADDOO  -- ANALOG ADD                 !B# 0220                                P-0 PCSRF4------.VO3AER
           !                                                     !                                       P-1 PCSRF5------.VO3B2R
           !                      X = A + B                      !                                       P-2 100.00------.C18F8R
           !                      __________                     !
           !                      !        !                     !
PCSRF4     !(P-0) A               !   !    !              X (P-1)!PCSRF5
-----------!--------------------->!  -+-   !->-------------------!------------
           !                      !   !    !                     !
           !                      !________!                     !
           !                          ^                          !
100.00     !(P-2) B                   !                          !
-----------!--------------------------+                          !
           !                                                     !
           !                                                     !
           !                                                     !
           !                                                     !
           !                                                     !
...........!(LI-1)                                         (LO-1)!
-----------!-----------------> ENABLE >--------------------------!------------
           +-----------------------------------------------------+


PCSRF4------.VO3AER  *04:0210
PCSRF5------.VO3B2R   04:0240   04:0250    04:0260    04:0270    04:0280


NAME        ADDRESS   VALUE    DEVTYP LOCATION PAGE#   DESCRIPTION
----        -------   -----    ------ -------- -----   -----------
PCSRF4------.VO3AER                                    PR CTRL - SPD REF CALC FOR GEAR IN SPD 4
PCSRF5------.VO3B2R                                    PR CTRL - SPD REF CALC FOR GEAR IN SPD 5
```

```
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************************************************************************************************************************
```

```
                                                                                                ===================  ========
                                                                                                SEGMENT:04/BLOCK:0240  PG: 0077
                                                                                                ===================  ========

+++++++++++++++++++++++++++++++++++++++++++++++++++
+++++++++++++++++++++++++++++++++++++++++++++++++++
+++++++++  FIND RANGE OF SPEED REFERENCE IN
+++++++++  10 PERCENT INCREMENTS
+++++++++++++++++++++++++++++++++++++++++++++++++++
+++++++++++++++++++++++++++++++++++++++++++++++++++


VEHICLE SPEED REFERENCE IS GREATER THAN 00% OF MAX

                                                                                                         BLK ACMP00
           +-----------------------------------------------------+                                       B#  0240
           !             ACMP00  -- ANALOG COMPARE               !B# 0240                                P-0 PCSRF5------.V03B2R
           !              X = COMPARISON OF A TO B               !                                       P-1 KSP00--------.C02FER
           !               _______________________               !                                       P-2 4------------.C18F6C
           !               !     COMPARE           !             !                                       STO SGT00--------.L013F
PCSRF5     !(P-0) A        !CODE!    A TO B        !       X (LO-1)!SGT00                                B#  0240
-----------!-------------->! - -!- - - - - - - - !->-------------!------------
           !               !  0 !      =           !             !
           !               !  1 !     < >          !             !
           !               !  2 !      <           !             !
KSP00      !(P-1) B        !  3 !      >           !             !
-----------!-------------->! 4  !      >=          !             !
           !               !  5 !      <=          !             !
           !               +---------------------+               !
4          !(P-2) CODE       ^                                   !
-----------!-----------------+                                   !
           !                                                     !
           !                                                     !
...........!(LI-1)                                               !
-----------!---------------------> ENABLE                        !
           +-----------------------------------------------------+


PCSRF5-------.V03B2R *04:0220    04:0250    04:0260    04:0270    04:0280
KSP00--------.C02FER  04:0350    07:0190    07:0300
SGT00--------.L013F   04:0350    04:0360


NAME        ADDRESS   VALUE    DEVTYP LOCATION PAGE#   DESCRIPTION
----        --------  -----    ------ -------- -----   -----------
PCSRF5-------.V03B2R                                   PR CTRL - SPD REF CALC FOR GEAR IN SPD 5
KSP00--------.C02FER  0.0                              PR CTRL - SPEED POINT CONSTANT, 00%
SGT00--------.L013F                                    PR CTRL - SPEED POINT >/= 00%
```

```
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*                      *  S&P_DRIVES_T  *                               *  NEXT PAGE: 0078                 PAGE: 0077  *
************************************************************************************************************************
```

```
=====================  ========
SEGMENT:04/BLOCK:0250  PG: 0078
=====================  ========

          BLK ACMPOO
          B#  0250
          P-0 PCSRF5-------.V03B2R
          P-1 KSP10--------.C0302R
          P-2 4------------.C18F6C
          STO SGT10--------.L0140
          B#  0250
```

```
VEHICLE SPEED REFERENCE IS GREATER THAN 10% OF MAX

           +-----------------------------------------------------+
           !             ACMPOO  -- ANALOG COMPARE               !B# 0250
           !              X = COMPARISON OF A TO B               !
           !               _______________________               !
           !               !     COMPARE         !               !
PCSRF5     !(P-0) A        !CODE!    A TO B      !       X (LO-1)!SGT10
-----------!-------------->! - -!- - - - - - - - !->-------------!------------
           !               !  0 !      =         !               !
           !               !  1 !     < >        !               !
           !               !  2 !      <         !               !
KSP10      !(P-1) B        !  3 !      >         !               !
-----------!-------------->! 4  !      >=        !               !
           !               !  5 !      <=        !               !
           !               +---------------------+               !
4          !(P-2) CODE       ^                                   !
-----------!-----------------+                                   !
...........!(LI-1)                                               !
-----------!---------------------> ENABLE                        !
           +-----------------------------------------------------+
```

```
=====================  ========
SEGMENT:04/BLOCK:0350  PG: 0076
=====================  ========
```

```
+++++++++++++++++++++++++++++++++++++++++++++++++++
+++++++++   MOVE APPROPRIATE TABLE TO WORKING
+++++++++   VARIABLE DEPENDING ON SPEED RANGE
+++++++++++++++++++++++++++++++++++++++++++++++++++
MOVE THE SPEED RANGE VALUES TO THE WORKING VARIABLES
SPEED IS BETWEEN 0 AND        10%
                                              +-----------------------+
 SGT00  SGT10                                 !            IMOVOO     !
+--] [--+--]/[--+-------+------+-------+------+ENABLE                 !
    *      *                                  !   INPUT LOGICALS      !
                                              !   FOR NEXT BLOCK      !
                                              +-----------------------+
           +-----------------------------------------------------+
           !             IMOVOO  -- MOVE DATA BLOCK              +!B# 0350
           !        Move multiple words from source to target    !
           !                      +---------+                    !
KSP00      !(P-0) SOURCE          ! Word    !       TARGET (P-1)!SPRG1
-----------!--------------------->! Transfer!->------------------!------------
           !                      +---------+                    !
4          !(P-2) LENGTH in words      !                         !
-----------!---------------------------+                         !
***-ENABLE !(LI-1)                                         (LO-1)!
-----------!---------------------> ENABLE >----------------------!------------
           +-----------------------------------------------------+
```

```
LD  SGT00--------.L013F
ANF SGT10--------.L0140
BLK IMOVOO
B#  0350
P-0 KSP00--------.C02FER
P-1 SPRG1--------.V03DCR
P-2 4------------.C18F6C
```

```
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*                    *  S&P_DRIVES_T *                              *  NEXT PAGE: 0079                    PAGE: 0078   *
************************************************************************************************************************
```

```
SGT00-------.L013F   *04:0240   04:0360
SGT10-------.L0140   *04:0250   04:0360    04:0370    04:0380    07:0140
KSP00-------.C02FER   04:0240   07:0190    07:0300
SPRG1-------.V03DCR  *04:0370  *04:0390   *04:0410   *04:0430   *04:0450
NAME        ADDRESS   VALUE    DEVTYP LOCATION PAGE#   DESCRIPTION
----        -------   -----    ------ -------- -----   -----------
SGT00-------.L013F                                     PR CTRL - SPEED POINT >/= 00%
SGT10-------.L0140                                     PR CTRL - SPEED POINT >/= 10%
KSP00-------.C02FER   0.0                              PR CTRL - SPEED POINT CONSTANT, 00%
SPRG1-------.V03DCR                                    PR CTRL - LOWER SPEED POINT VAR., #1
                                                                                                ====================  ========
                                                                                                SEGMENT:04/BLOCK:0360  PG: 0079
                                                                                                ====================  ========

MOVE THE APPROPRIATE TABLES TO THE WORKING TABLES
TORQUE AND POSITION TABLES FOR SPEED AT 00 %
TORQUE AND POSITION TABLES FOR SPEED AT 10 %
                                              +-----------------------+
 SGT00   SGT10                                !            IMOVOO     !
+--] [--+--]/[--+------+-------+-------+------+ENABLE                 !
    *      *                                  !   INPUT LOGICALS      !
                                              !   FOR NEXT BLOCK      !
                                              +-----------------------+
                                                                                                         LD  SGT00-------.L013F
           +------------------------------------------------------+                                      ANF SGT10-------.L0140
           !             IMOVOO  -- MOVE DATA BLOCK               +!B# 0360                              BLK IMOVOO
           !                                                      !                                      B#  0360
           !        Move multiple words from source to target     !                                      P-0 T2U1_1------.V0594R
           !                                                      !                                      P-1 PCTTB1------.V040CR
           !                      +----------+                    !                                      P-2 T2EST2------.V04D2C
           !                      !          !                    !
T2U1_1     !(P-0) SOURCE          !  Word    !        TARGET (P-1)!PCTTB1
-----------!--------------------->! Transfer!->-------------------!------------
           !                      +----------+                    !
T2EST2     !(P-2) LENGTH in words       !                         !
-----------!----------------------------+                         !
***-ENABLE !(LI-1)                                          (LO-1)!
-----------!---------------------> ENABLE >-----------------------!------------
           +------------------------------------------------------+
SGT00-------.L013F   *04:0240   04:0350
SGT10-------.L0140   *04:0250   04:0350    04:0370    04:0380    07:0140
T2U1_1------.V0594R   08:0600  *10:0250    10:0280    12:0430   *12:0820
PCTTB1------.V040CR  *04:0380  *04:0400   *04:0420   *04:0440   *04:0460
T2EST2------.V04D2C  *02:0070   04:0380    04:0400    04:0420    04:0440

NAME        ADDRESS   VALUE    DEVTYP LOCATION PAGE#   DESCRIPTION
----        -------   -----    ------ -------- -----   -----------
SGT00-------.L013F                                     PR CTRL - SPEED POINT >/= 00%
SGT10-------.L0140                                     PR CTRL - SPEED POINT >/= 10%
T2U1_1------.V0594R                                    TBL 2,ITEM 1,INUSE TORQUE 1, (PU)
PCTTB1------.V040CR                                    PR CTRL - LOWER SPD PT TRQ TABLE 1A
T2EST2------.V04D2C                                    TBLES - TABLE 2, SPD PT ENTRY SIZE, BYTES
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*                    *  S&P_DRIVES_T   *                             *  NEXT PAGE: 0080                     PAGE: 0079   *
************************************************************************************************************************
```

```
                                                                                                ===================== ========
                                                                                                SEGMENT:04/BLOCK:0370  PG: 0080
                                                                                                ===================== ========
MOVE THE SPEED RANGE VALUES TO THE WORKING VARIABLES
SPEED IS BETWEEN 10 AND 20%
                                              +-----------------------+
 SGT10  SGT20                                 !            IMOVOO     !
+--] [--+--]/[--+------+-------+-------+------+ENABLE                 !
    *      *                                  !   INPUT LOGICALS      !
                                              !   FOR NEXT BLOCK      !
                                              +-----------------------+
                                                                                                         LD  SGT10-------.L0140
           +-----------------------------------------------------+                                       ANF SGT20-------.L0141
           !             IMOVOO  -- MOVE DATA BLOCK              +!B# 0370                               BLK IMOVOO
           !                                                     !                                       B#  0370
           !        Move multiple words from source to target    !                                       P-0 KSP10-------.C0302R
           !                                                     !                                       P-1 SPRG1-------.V03DCR
           !                      +---------+                    !                                       P-2 4-----------.C18F6C
           !                      !         !                    !
           !                      !         !                    !
KSP10      !(P-0) SOURCE          !  Word   !        TARGET (P-1)!SPRG1
-----------!--------------------->! Transfer!->------------------!------------
           !                      !         !                    !
           !                      +---------+                    !
           !                           ^                         !
4          !(P-2) LENGTH in words      !                         !
-----------!---------------------------+                         !
           !                                                     !
           !                                                     !
           !                                                     !
***-ENABLE !(LI-1)                                         (LO-1)!
-----------!---------------------> ENABLE >----------------------!------------
           +-----------------------------------------------------+

SGT10-------.L0140   *04:0250   04:0350    04:0360    04:0380    07:0140
SGT20-------.L0141   *04:0260   04:0380    04:0390    04:0400
KSP10-------.C0302R   04:0250   07:0200    07:0320
SPRG1-------.V03DCR  *04:0350  *04:0390   *04:0410   *04:0430   *04:0450

NAME        ADDRESS   VALUE    DEVTYP LOCATION PAGE#   DESCRIPTION
----        --------  -----    ------ -------- -----   -----------
SGT10-------.L0140                                     PR CTRL - SPEED POINT >/= 10%
SGT20-------.L0141                                     PR CTRL - SPEED POINT >/= 20%
KSP10-------.C0302R   10.0                             PR CTRL - SPEED POINT CONSTANT, 10%
SPRG1-------.V03DCR                                    PR CTRL - LOWER SPEED POINT VAR., #1
```

```
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*                    *  S&P_DRIVES_T *                              *  NEXT PAGE: 0081                    PAGE: 0080    *
*************************************************************************************************************************
```

```
                                                                                                ====================  ========
                                                                                                SEGMENT:04/BLOCK:0380  PG: 0081
                                                                                                ====================  ========
MOVE THE APPROPRIATE TABLES TO THE WORKING TABLES

TORQUE AND POSITION TABLES FOR SPEED AT 10 %
TORQUE AND POSITION TABLES FOR SPEED AT 20 %

 SGT10  SGT20                                +------------------------+
                                             !            IMOVOO      !
+--] [--+--]/[--+---------------+-------+-------+ENABLE                !
    *      *                                 !   INPUT LOGICALS       !
                                             !   FOR NEXT BLOCK       !
                                             !                        !
                                             +------------------------+
                                                                                                        LD  SGT10-------.L0140
           +------------------------------------------------------+                                     ANF SGT20-------.L0141
           !            IMOVOO  -- MOVE DATA BLOCK                +!B# 0380                              BLK IMOVOO
           !                                                      !                                     B#  0380
           !       Move multiple words from source to target      !                                     P-0 T2U2_1------.V05ECR
           !                                                      !                                     P-1 PCTTB1------.V040CR
           !                      +----------+                    !                                     P-2 T2EST2------.V04D2C
           !                      !          !                    !
           !                      !          !                    !
T2U2_1     !(P-0) SOURCE          !  Word    !       TARGET (P-1)!PCTTB1
-----------!--------------------->! Transfer!->-------------------!------------
           !                      !          !                    !
           !                      +----------+                    !
           !                                 -                    !
T2EST2     !(P-2) LENGTH in words            !                    !
-----------!---------------------------------+                    !
           !                                                      !
           !                                                      !
           !                                                      !
***-ENABLE !(LI-1)                                          (LO-1)!
-----------!---------------------> ENABLE >-----------------------!------------
           +------------------------------------------------------+
SGT10-------.L0140   *04:0250   04:0350    04:0360    04:0370    07:0140
SGT20-------.L0141   *04:0260   04:0370    04:0390    04:0400
PCTTB1------.V040CR  *04:0360  *04:0400   *04:0420   *04:0440   *04:0460
T2EST2------.V04D2C  *02:0070   04:0360    04:0400    04:0420    04:0440
NAME         ADDRESS  VALUE    DEVTYP LOCATION PAGE#   DESCRIPTION
----         -------  -----    ------ -------- -----   -----------
SGT10-------.L0140                                     PR CTRL - SPEED POINT >/= 10%
SGT20-------.L0141                                     PR CTRL - SPEED POINT >/= 20%
T2U2_1------.V05ECR                                    TBL 2,ITEM 1,INUSE TORQUE 2, (PU)
PCTTB1------.V040CR                                    PR CTRL - LOWER SPD PT TRQ TABLE 1A
T2EST2------.V04D2C                                    TBLES - TABLE 2, SPD PT ENTRY SIZE, BYTES

     ***************  NOTE: THE ABOVE TWO RUNGS ARE REPEATED FOR THE REST OF THE SPEED RANGES **************

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*                     *  S&P_DRIVES_T  *                              *  NEXT PAGE: 0082          PAGE: 0081   *
*****************************************************************************************************************
```

```
+++++++++++++++++++++++++++++++++++++++++++++++++++
+++++++++  LINEAR INTERPOLATORS AND CALCS FOR
+++++++++  FINAL PREDICTIVE CONTROL POSITION CMMD
+++++++++++++++++++++++++++++++++++++++++++++++++++
LINEAR INTERPOLATORS - UPPER AND LOWER SPEED POINTS
===================================================

LINEAR INTERPOLATOR FOR LOWER SPEED POINT

INPUT TABLE IS TORQUE
OUTPUT TABLE IS POSITION
           +-----------------------------------------------------+
           !        ALIPOO  -- LINEAR INTERPOLATER               ! B# 0690
           !                                                     !
           !          Interpolate using a table lookup           !
           !                                                     !
           !            +--------+       +---------+             !
VTQRFC     !(P-0) INPUT !        !       !         ! OUTPUT (P-5)!PCLPOS
-----------!----------->!   X    !======>!  F(X)   !-------------!----------
           !            !        !       !         !  INDEX (P-4)!PCLIDX
           !            !        !       !         !-------------!----------
           !            +--------+       +---------+             !
PCTTB1     !(P-2) ARGTAB    !<--------+-------->!                !
-----------!----------------+         !         !                !
KT2SPN     !(P-1) TABSIZ              !         !                !
-----------!--------------------------+         !                !
PCPTB1     !(P-3) FNCTAB                        !                !
-----------!------------------------------------+                !
           !                                                     !
PCSTRT     !(LI-1)                                         (LO-1)!
-----------!--------------------> ENABLE >-----------------------!-----------
           +-----------------------------------------------------+

PCSTRT------.L0138   04:0120 *04:0120    04:0130    04:0200    04:0570
VTQRFC------.V03E4R *04:0660  04:0700
KT2SPN------.C0330C  04:0700  07:0520    07:0530    07:0540    07:0550
PCTTB1------.V040CR *04:0360 *04:0380   *04:0400   *04:0420   *04:0440
PCLPOS------.V03E8R  04:0720

NAME        ADDRESS   VALUE    DEVTYP LOCATION PAGE#   DESCRIPTION
----        -------   -----    ------ -------- -----   -----------
PCSTRT------.L0138                                     PR CTRL - START AND RUN PREDICTIVE CONTROL
VTQRFC------.V03E4R                                    PR CTRL - CALC VEHICLE TORQUE REF.
KT2SPN------.C0330C   11                               TBLES - TABLE 2, NUMBER OF SPEED POINT ENTRY'S
PCTTB1------.V040CR                                    PR CTRL - LOWER SPD PT TRQ TABLE 1A
PCPTB1------.V0438R                                    PR CTRL - LOWER SPD PT POS TABLE 1A
PCLIDX------.V03F0C                                    PR CTRL - LOWER SPD PT LINEAR INTER INDEX
PCLPOS------.V03E8R                                    PR CTRL - LOWER SPD PT THR POSITION
```

```
LD  PCSTRT------.L0138
BLK ALIPOO
B#  0690
P-0 VTQRFC------.V03E4R
P-1 KT2SPN------.C0330C
P-2 PCTTB1------.V040CR
P-3 PCPTB1------.V0438R
P-4 PCLIDX------.V03F0C
P-5 PCLPOS------.V03E8R
```

```
LINEAR INTERPOLATOR FOR UPPER SPEED POINT

INPUT TABLE IS TORQUE
OUTPUT TABLE IS POSITION

                                                                                          LD  PCSTRT------.L0138
                                                                                          BLK ALIPOO
                                                                                          B#  0700
                                                                                          P-0 VTQRFC------.V03E4R
                                                                                          P-1 KT2SPN------.C0330C
                                                                                          P-2 PCTTB2------.V0464R
                                                                                          P-3 PCPTB2------.V0490R
                                                                                          P-4 PCUIDX------.V03F2C
                                                                                          P-5 PCUPOS------.V03ECR

           +-----------------------------------------------------+
           !        ALIPOO  -- LINEAR INTERPOLATER               ! B# 0700
           !                                                     !
           !          Interpolate using a table lookup           !
           !                                                     !
           !            +--------+       +---------+             !
VTQRFC     !(P-0) INPUT !        !       !         ! OUTPUT (P-5)!PCUPOS
-----------!----------->!    X   !======>!  F(X)   !-------------!----------
           !            !        !       !         !  INDEX (P-4)!PCUIDX
           !            !        !       !         !-------------!----------
           !            +--------+       +---------+             !
PCTTB2     !(P-2) ARGTAB    !<-------+------->!                  !
-----------!----------------+        !        !                  !
KT2SPN     !(P-1) TABSIZ             !        !                  !
-----------!-------------------------+        !                  !
PCPTB2     !(P-3) FNCTAB                      !                  !
-----------!----------------------------------+                  !
           !                                                     !
PCSTRT     !(LI-1)                                         (LO-1)!
-----------!--------------------> ENABLE >-----------------------!-----------
           +-----------------------------------------------------+

PCSTRT------.L0138    04:0120  *04:0120    04:0130    04:0200    04:0570
VTQRFC------.V03E4R  *04:0660   04:0690
KT2SPN------.C0330C   04:0690   07:0520    07:0530    07:0540    07:0550
PCUPOS------.V03ECR   04:0720   04:0770

NAME         ADDRESS    VALUE     DEVTYP LOCATION PAGE#   DESCRIPTION
----         -------    -----     ------ -------- -----   -----------
PCSTRT------.L0138                                        PR CTRL - START AND RUN PREDICTIVE CONTROL
VTQRFC------.V03E4R                                       PR CTRL - CALC VEHICLE TORQUE REF.
KT2SPN------.C0330C     11                                TBLES - TABLE 2, NUMBER OF SPEED POINT ENTRY'S
PCTTB2------.V0464R                                       PR CTRL - UPPER SPD PT TRQ TABLE 2A
PCPTB2------.V0490R                                       PR CTRL - UPPER SPD PT POS TABLE 2A
PCUIDX------.V03F2C                                       PR CTRL - UPPER SPD PT LINEAR INTER INDEX
PCUPOS------.V03ECR                                       PR CTRL - UPPER SPD PT THR POSITION
```

```
CALCULATE FINAL POSITION COMMAND BETWEEN UPPER AND LOWER POSITIONS
==================================================================
==================================================================


FIND THE DIFFERENCE BETWEEN THE UPPER AND LOWER POSITION COMMAND
```

```
LD  PCSTRT-------.L0138
BLK ASUB00
B#  0720
P-0 PCUPOS-------.V03ECR
P-1 PCPOS1-------.V03F4R
P-2 PCLPOS-------.V03E8R
```

```
           +-----------------------------------------------------+
           !             ASUB00  -- ANALOG SUBTRACT              !B# 0720
           !                                                     !
           !                   X  = A - B                        !
           !                                                     !
           !                                                     !
           !                     __________                      !
           !                     !         !                     !
PCUPOS     !(P-0) A              !         !              X (P-1)!PCPOS1
-----------!-------------------->!  ---    !->-------------------!------------
           !                     !         !                     !
           !                     !_________!                     !
           !                        ^                            !
           !                        !                            !
PCLPOS     !(P-2) B                 !                            !
-----------!------------------------+                            !
           !                                                     !
           !                                                     !
           !                                                     !
PCSTRT     !(LI-1)                                         (LO-1)!
-----------!-------------------> ENABLE >------------------------!------------
           +-----------------------------------------------------+
```

```
PCSTRT-------.L0138    04:0120  *04:0120    04:0130    04:0200    04:0570
PCUPOS-------.V03ECR  *04:0700   04:0770
PCPOS1-------.V03F4R   04:0750
PCLPOS-------.V03E8R  *04:0690


NAME          ADDRESS    VALUE    DEVTYP LOCATION PAGE#   DESCRIPTION
----          -------    -----    ------ -------- -----   -----------
PCSTRT-------.L0138                                       PR CTRL - START AND RUN PREDICTIVE CONTROL
PCUPOS-------.V03ECR                                      PR CTRL - UPPER SPD PT THR POSITION
PCPOS1-------.V03F4R                                      PR CTRL - THR POS INTERMEDIATE CALC 1
PCLPOS-------.V03E8R                                      PR CTRL - LOWER SPD PT THR POSITION
```

```
************************************************************************************************
*                    *                  *  COPYRIGHT (C) 1988,  BY   *  SYSTEM:FORD_THROTTLE      *
* DATE:03/18/88      *  REQUISITION     *  GENERAL ELECTRIC COMPANY  *                            *
* AUTHOR :DR_SOCKY   *  541-DJ-43789    *  DRIVE SYSTEMS DEPARTMENT  ******************************
*                    *  D.S.D           *  SALEM, VA     USA         *  DRAWING : 23788030        *
*                    *  S&P_DRIVES_T    *                            *  NEXT PAGE: 0085  PAGE: 0084 *
************************************************************************************************
```

```
                                                                                                  ===================  ========
                                                                                                  SEGMENT:04/BLOCK:0730  PG: 0085
                                                                                                  ===================  ========
FIND THE DIFFERENCE BETWEEN THE UPPER SPEED POINT AND THE ACTUAL
SPEED REFERENCE.
                                                                                                          LD  PCSTRT------.L0138
           +-------------------------------------------------------+                                      BLK ASUB00
           !              ASUB00  -- ANALOG SUBTRACT               !B# 0730                               B#  0730
           !                                                       !                                      P-0 SPRG2-------.V03E0R
           !                    X  = A - B                         !                                      P-1 PCPOS2------.V03F8R
           !                                                       !                                      P-2 PCSRF5------.V03B2R
           !                          __________                   !
SPRG2      !(P-0) A                  !          !        X (P-1)!PCPOS2
-----------!------------------------>!   ---    !->--------------------!------------
          .!                         !__________!                  !
           !                              -                        !
PCSRF5     !(P-2) B                       !                        !
-----------!------------------------------+                        !
           !                                                       !
PCSTRT     !(LI-1)                                           (LO-1)!
-----------!-------------------> ENABLE >--------------------------!------------
           +-------------------------------------------------------+
PCSTRT------.L0138    04:0120  *04:0120    04:0130    04:0200    04:0570
SPRG2-------.V03E0R   04:0740
PCPOS2------.V03F8R   04:0750
PCSRF5------.V03B2R  *04:0220   04:0240    04:0250    04:0260    04:0270
NAME         ADDRESS  VALUE    DEVTYP LOCATION PAGE#   DESCRIPTION
----         -------  -----    ------ -------- -----   -----------
PCSTRT------.L0138                                     PR CTRL - START AND RUN PREDICTIVE CONTROL
SPRG2-------.V03E0R                                    PR CTRL - UPPER SPEED POINT VAR., #2
PCPOS2------.V03F8R                                    PR CTRL - THR POS INTERMEDIATE CALC 2
PCSRF5------.V03B2R                                    PR CTRL - SPD REF CALC FOR GEAR IN SPD 5
                                                                                                  ===================  ========
                                                                                                  SEGMENT:04/BLOCK:0740  PG: 0094
                                                                                                  ===================  ========
FIND THE DIFFERENCE BETWEEN THE UPPER SPEED POINT AND THE LOWER   SPEED POINT.
                                                                                                          LD  PCSTRT------.L0138
           +-------------------------------------------------------+                                      BLK ASUB00
           !              ASUB00  -- ANALOG SUBTRACT               !B# 0740                               B#  0740
           !                    X  = A - B                         !                                      P-0 SPRG2-------.V03E0R
           !                          __________                   !                                      P-1 PCPOS3------.V03FCR
SPRG2      !(P-0) A                  !          !        X (P-1)!PCPOS3                                   P-2 SPRG1-------.V03DCR
-----------!------------------------>!   ---    !->--------------------!------------
           !                         !__________!                  !
           !                              -                        !
SPRG1      !(P-2) B                       !                        !
-----------!------------------------------+                        !
           !                                                       !
PCSTRT     !(LI-1)                                           (LO-1)!
-----------!-------------------> ENABLE >--------------------------!------------
           +-------------------------------------------------------+
**************************************************************************************************************************
*                    *                *  COPYRIGHT (C) 1988,  BY    *  SYSTEM:FORD_THROTTLE                                *
* DATE:03/18/88      *  REQUISITION   *  GENERAL ELECTRIC COMPANY   *                                                      *
* AUTHOR :DR_SOCKY   *  541-DJ-43789  *  DRIVE SYSTEMS DEPARTMENT   ********************************************************
*                    *  D.S.D         *  SALEM, VA     USA          *  DRAWING : 237B8030                                  *
*                    *  S&P_DRIVES_T  *                             *  NEXT PAGE: 0086                        PAGE: 0085   *
**************************************************************************************************************************
```

```
PCSTRT------.L0138    04:0120  *04:0120    04:0130    04:0200    04:0570
SPRG2-------.V03E0R   04:0730
PCPOS3------.V03FCR   04:0760
SPRG1-------.V03DCR  *04:0350  *04:0370   *04:0390   *04:0410   *04:0430

NAME        ADDRESS   VALUE    DEVTYP LOCATION PAGE#   DESCRIPTION
----        -------   -----    ------ -------- -----   -----------
PCPOS3------.V03FCR                                    PR CTRL - THR POS INTERMEDIATE CALC 3
SPRG1-------.V03DCR                                    PR CTRL - LOWER SPEED POINT VAR., #1
                                                                                                =====================  ========
                                                                                                SEGMENT:04/BLOCK:0750  PG: 0086
                                                                                                =====================  ========
MULTIPLY PCPOS1 BY PCPOS2

                                                                                                         LD  PCSTRT------.L0138
           +-----------------------------------------------------+                                       BLK AMPY00
           !             AMPY00  -- ANALOG MULTIPLY              !B# 0750                                B#  0750
           !                                                     !                                       P-0 PCPOS1------.V03F4R
           !                      X = A * B                      !                                       P-1 PCPOS4------.V0400R
           !                                                     !                                       P-2 PCPOS2------.V03F8R
           !                       __________                    !
           !                       !        !                    !
PCPOS1     !(P-0) A                !  \ /   !            X  (P-1)!PCPOS4
-----------!---------------------->!   X    !->------------------!------------
           !                       !  / \   !                    !
           !                       !________!                    !
           !                           ^                         !
           !                           !                         !
PCPOS2     !(P-2) B                    !                         !
-----------!---------------------------+                         !
           !                                                     !
           !                                                     !
           !                                                     !
PCSTRT     !(LI-1)                                         (LO-1)!
-----------!--------------------> ENABLE >-----------------------!------------
           +-----------------------------------------------------+

PCSTRT------.L0138    04:0120  *04:0120    04:0130    04:0200    04:0570
PCPOS1------.V03F4R  *04:0720
PCPOS4------.V0400R   04:0760
PCPOS2------.V03F8R  *04:0730

NAME        ADDRESS   VALUE    DEVTYP LOCATION PAGE#   DESCRIPTION
----        -------   -----    ------ -------- -----   -----------
PCSTRT------.L0138                                     PR CTRL - START AND RUN PREDICTIVE CONTROL
PCPOS1------.V03F4R                                    PR CTRL - THR POS INTERMEDIATE CALC 1
PCPOS4------.V0400R                                    PR CTRL - THR POS INTERMEDIATE CALC 4
PCPOS2------.V03F8R                                    PR CTRL - THR POS INTERMEDIATE CALC 2

************************************************************************************************************************
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* DATE:03/18/88      *  REQUISITION  *   GENERAL ELECTRIC COMPANY   *                                                  *
* AUTHOR :DR_SOCKY   *  541-DJ-43789 *   DRIVE SYSTEMS DEPARTMENT   ****************************************************
*                    *  D.S.D        *   SALEM, VA    USA           *  DRAWING : 237B8030                              *
*                    *  S&P_DRIVES_T *                              *  NEXT PAGE: 0087                    PAGE: 0086   *
************************************************************************************************************************
```

```
DIVIDE PCPOS4 BY PCPOS3
```

```
LD  PCSTRT-------.L0138
BLK ADVD00
B#  0760
P-0 PCPOS4-------.V0400R
P-1 PCPOS5-------.V0404R
P-2 PCPOS3-------.V03FCR
```

```
            +---------------------------------------------------------+
            !              ADVD00  -- ANALOG DIVIDE                   !B# 0760
            !                                                         !
            !                        X = A / B                        !
            !                                                         !
            !                        ___________                      !
            !                        !         !                      !
PCPOS4      !(P-0) A                 !    o    !               X (P-1)!PCPOS5
------------!----------------------->!   ---   !->--------------------!------------
            !                        !    o    !                      !
            !                        !_________!                      !
            !                             -                           !
            !                             !                           !
            !                             !                           !
PCPOS3      !(P-2) B                      !                           !
------------!-----------------------------+                           !
            !                                                         !
            !                                                         !
            !                                                         !
PCSTRT      !(LI-1)                                             (LO-1)!
------------!---------------------> ENABLE >--------------------------!------------
            +---------------------------------------------------------+
```

```
PCSTRT-------.L0138    04:0120  *04:0120    04:0130     04:0200     04:0570
PCPOS4-------.V0400R  *04:0750
PCPOS5-------.V0404R   04:0770
PCPOS3-------.V03FCR  *04:0740
```

```
NAME         ADDRESS    VALUE     DEVTYP LOCATION PAGE#   DESCRIPTION
----         -------    -----     ------ -------- -----   -----------
PCSTRT-------.L0138                                       PR CTRL - START AND RUN PREDICTIVE CONTROL
PCPOS4-------.V0400R                                      PR CTRL - THR POS INTERMEDIATE CALC 4
PCPOS5-------.V0404R                                      PR CTRL - THR POS INTERMEDIATE CALC 5
PCPOS3-------.V03FCR                                      PR CTRL - THR POS INTERMEDIATE CALC 3
```

FIND THE FINAL THROTTLE POSITION COMMAND

```
                                                                           LD  PCSTRT-------.L0138
           +-----------------------------------------------------+         BLK ASUB00
           !             ASUB00  -- ANALOG SUBTRACT              !B# 0770  B#  0770
           !                                                     !         P-0 PCUPOS-------.V03ECR
           !                    X  = A - B                       !         P-1 PCPOSC-------.V0408R
           !                                                     !         P-2 PCPOS5-------.V0404R
           !                      __________                     !         STO PCCDN--------.L0139
           !                      !        !                     !         B#  0770
PCUPOS     !(P-0) A               !        !           X (P-1)!PCPOSC
-----------!--------------------->!  ---   !->-------------------!------------
           !                      !        !                     !
           !                      !________!                     !
           !                          ^                          !
           !                          !                          !
PCPOS5     !(P-2) B                   !                          !
-----------!--------------------------+                          !
           !                                                     !
           !                                                     !
           !                                                     !
PCSTRT     !(LI-1)                                       (LO-1)!PCCDN
-----------!--------------------> ENABLE >-----------------------!------------
           +-----------------------------------------------------+

PCSTRT-------.L0138    04:0120  *04:0120    04:0130    04:0200    04:0570
PCUPOS-------.V03ECR  *04:0700   04:0720
PCPOSC-------.V0408R   05:1430
PCPOS5-------.V0404R  *04:0760
PCCDN--------.L0139    04:0130

NAME         ADDRESS   VALUE    DEVTYP LOCATION PAGE#   DESCRIPTION
----         -------   -----    ------ -------- -----   -----------
PCSTRT-------.L0138                                     PR CTRL - START AND RUN PREDICTIVE CONTROL
PCUPOS-------.V03ECR                                    PR CTRL - UPPER SPD PT THR POSITION
PCPOSC-------.V0408R                                    PR CTRL - THROTTLE POSITION COMMAND (PU)
PCPOS5-------.V0404R                                    PR CTRL - THR POS INTERMEDIATE CALC 5
PCCDN--------.L0139                                     PR CTRL - PREDICTIVE CONTROL CALCS DONE
```

THIS COMPLETES THE CALCULATIONS FOR THE PREDICTIVE CONTROL. THE VARIABLE "PCPOSC" IS USED IN THE REGULATING SEGMENT AS THE POSITION COMMAND WHICH IS SENT TO THE INDEXER.

APPENDIX C

Additional simulation test results

The following figures show additional test results for the predictive control using the software simulation. These results show further details, and are included here to supplement the results presented in chapter four.

There are a total of thirteen strip chart recordings, grouped as explained below:

Group 1: Figure C-1, C-2, and C-3

These are tests at a lower speed range of 40 to 50 percent, with a fixed torque reference of 24 percent. Inertia compensation is switched out and in between tests. The first set of traces (figure C-1) is for just the speed regulator, while the next two figures are traces when the predictive control is enabled.

Group 2: Figure C-4 through C-7

These four figures are the same as those in group one except a higher speed range of 70 to 80 percent is used. Also, a slightly lower torque is used, sixteen percent.

Group 3: Figure C-8 through C-9

These are tests using the road load equation. Figure C-8 is for only the speed regulator, while the next is for the predictive control. A slight grade (hill) was included in the road load equation in order to increase the torque requirements. The speed range is from 30 percent to 70 percent speed, then back to two percent speed.

Group 4: Figure C-10 through C-13

These strip chart recordings are the same as those of group three except that two different speed ranges are included, and the grade was set for zero.

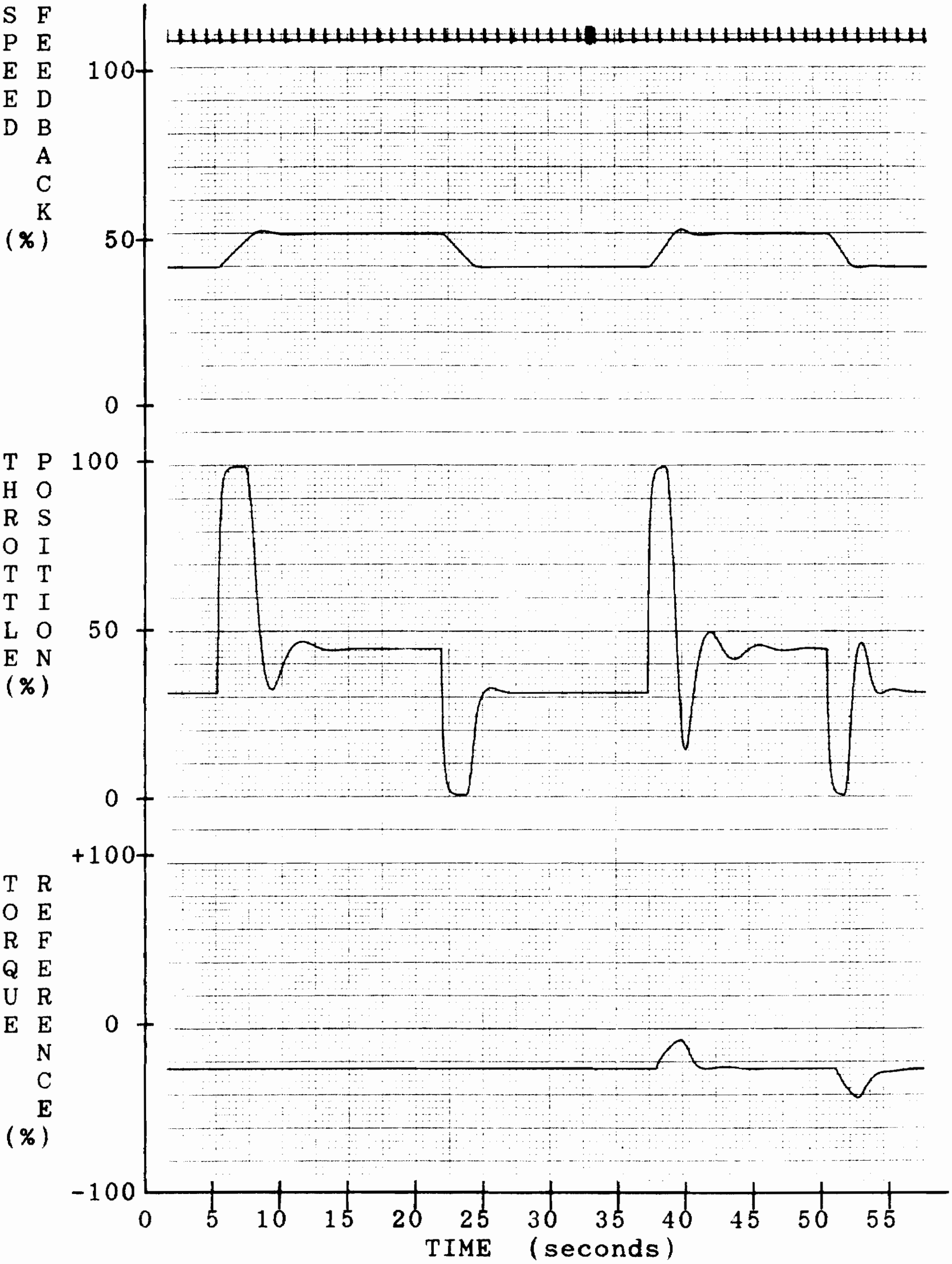

FIGURE C-1

SPEED REGULATOR, WITHOUT AND WITH INERTIA COMP.

LOW SPEED RANGE

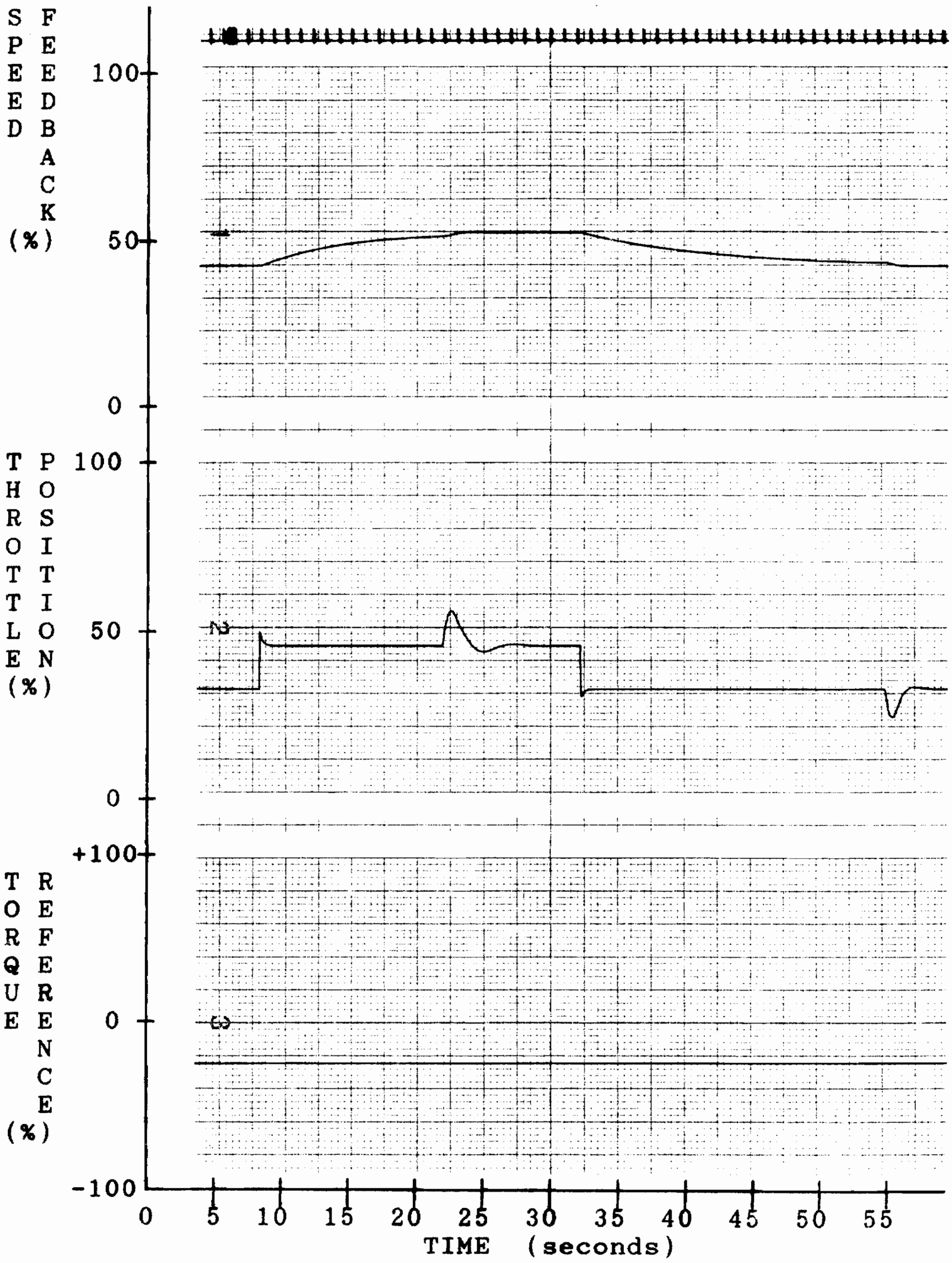

FIGURE C-2

PREDICTIVE CONTROL, NO INERTIA COMPENSATION

LOW SPEED RANGE

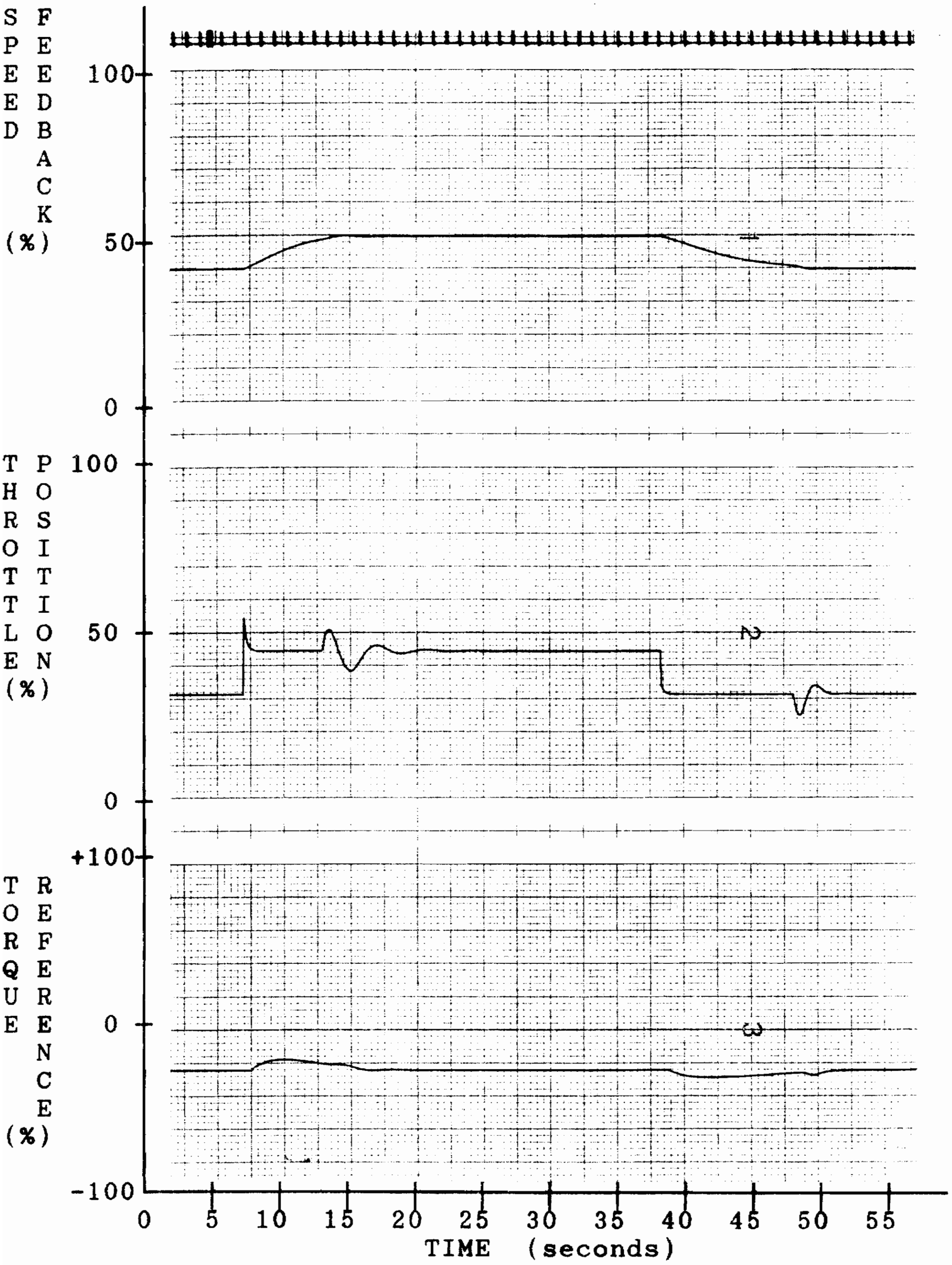

FIGURE C-3

<u>PREDICTIVE CONTROL, INERTIA COMPENSATION</u>

<u>LOW SPEED RANGE</u>

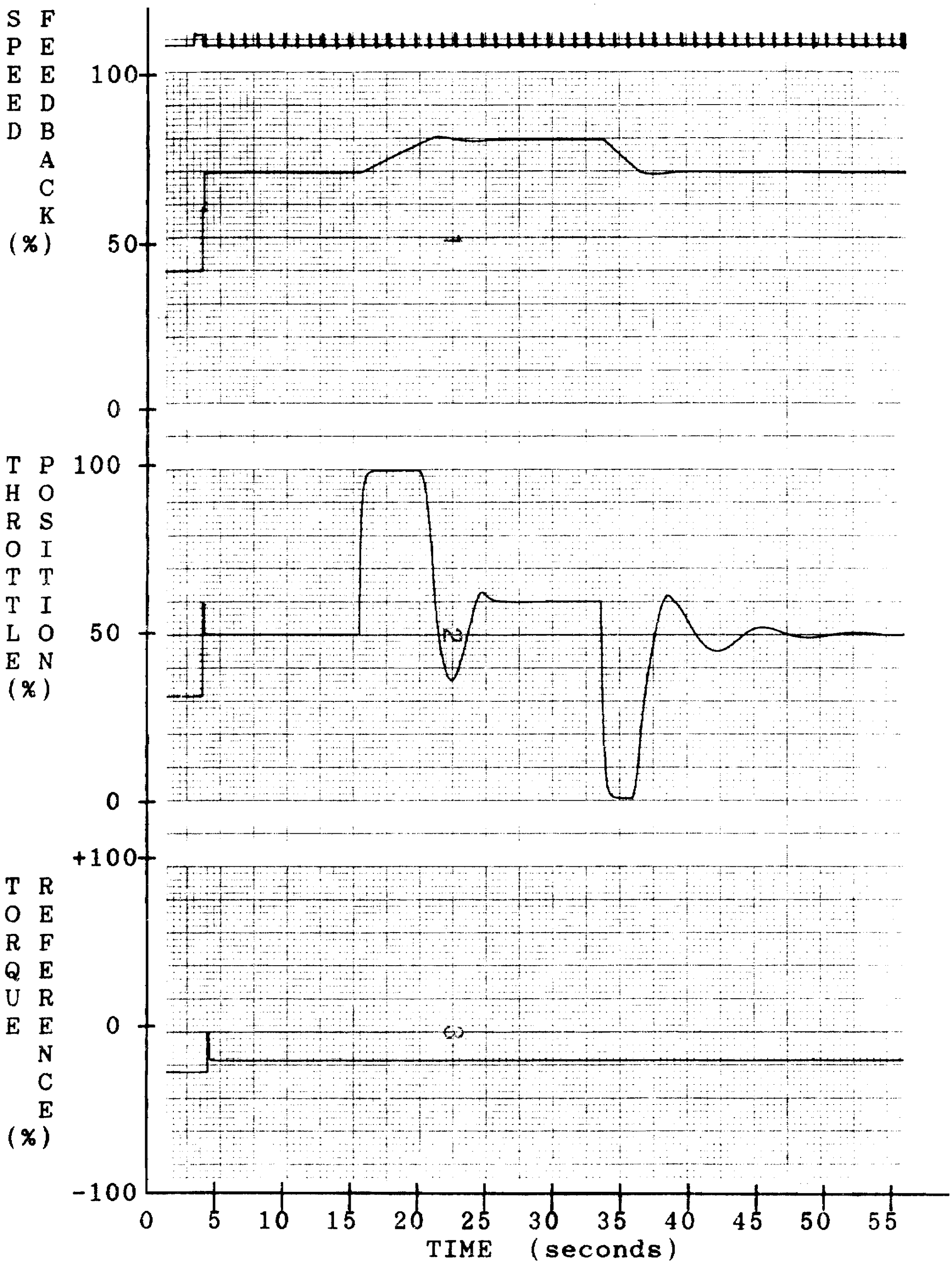

FIGURE C-4

SPEED REGULATOR, NO INERTIA COMPENSATION

HIGH SPEED RANGE

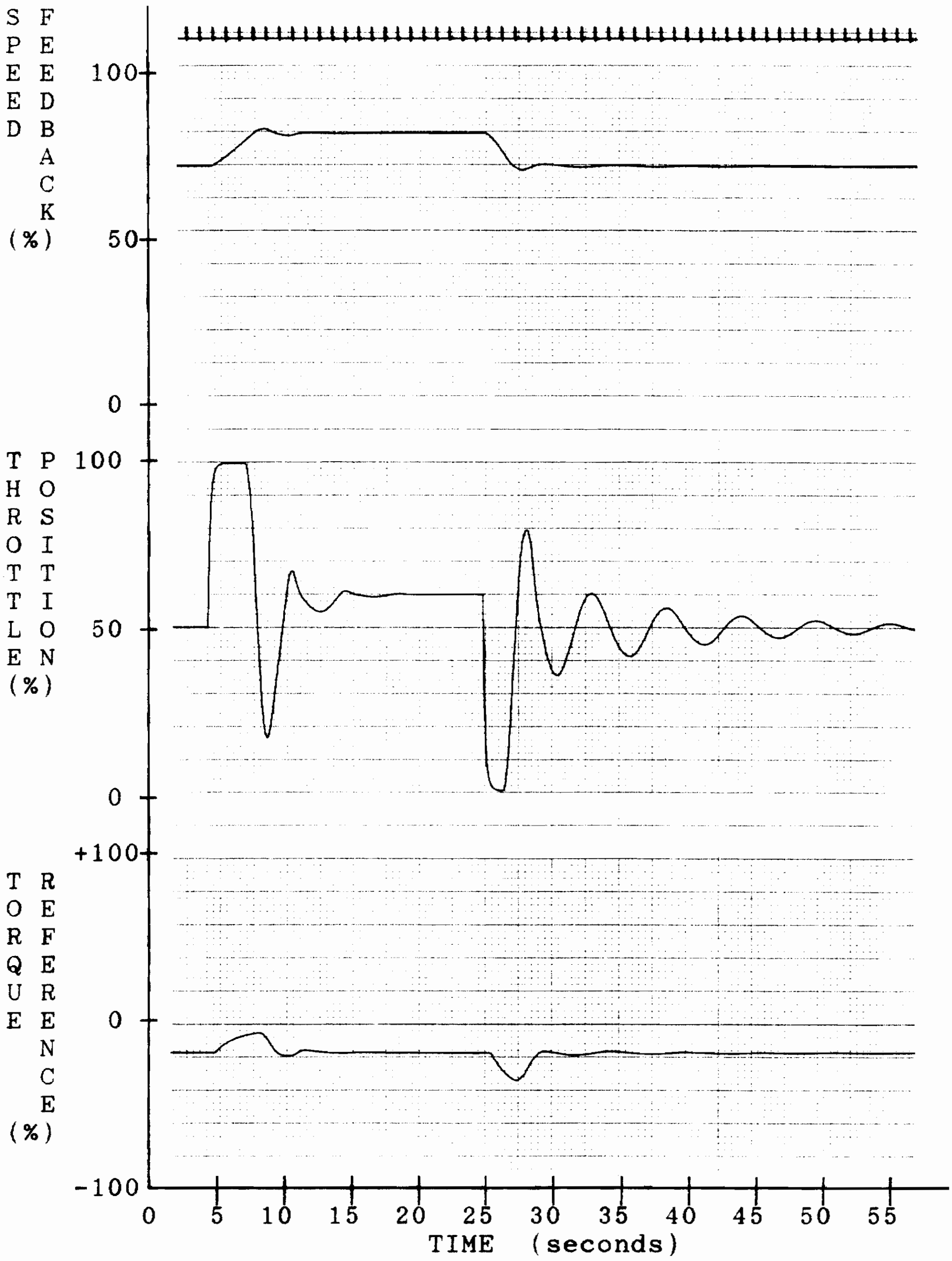

FIGURE C-5

SPEED REGULATOR, INERTIA COMPENSATION

HIGH SPEED RANGE

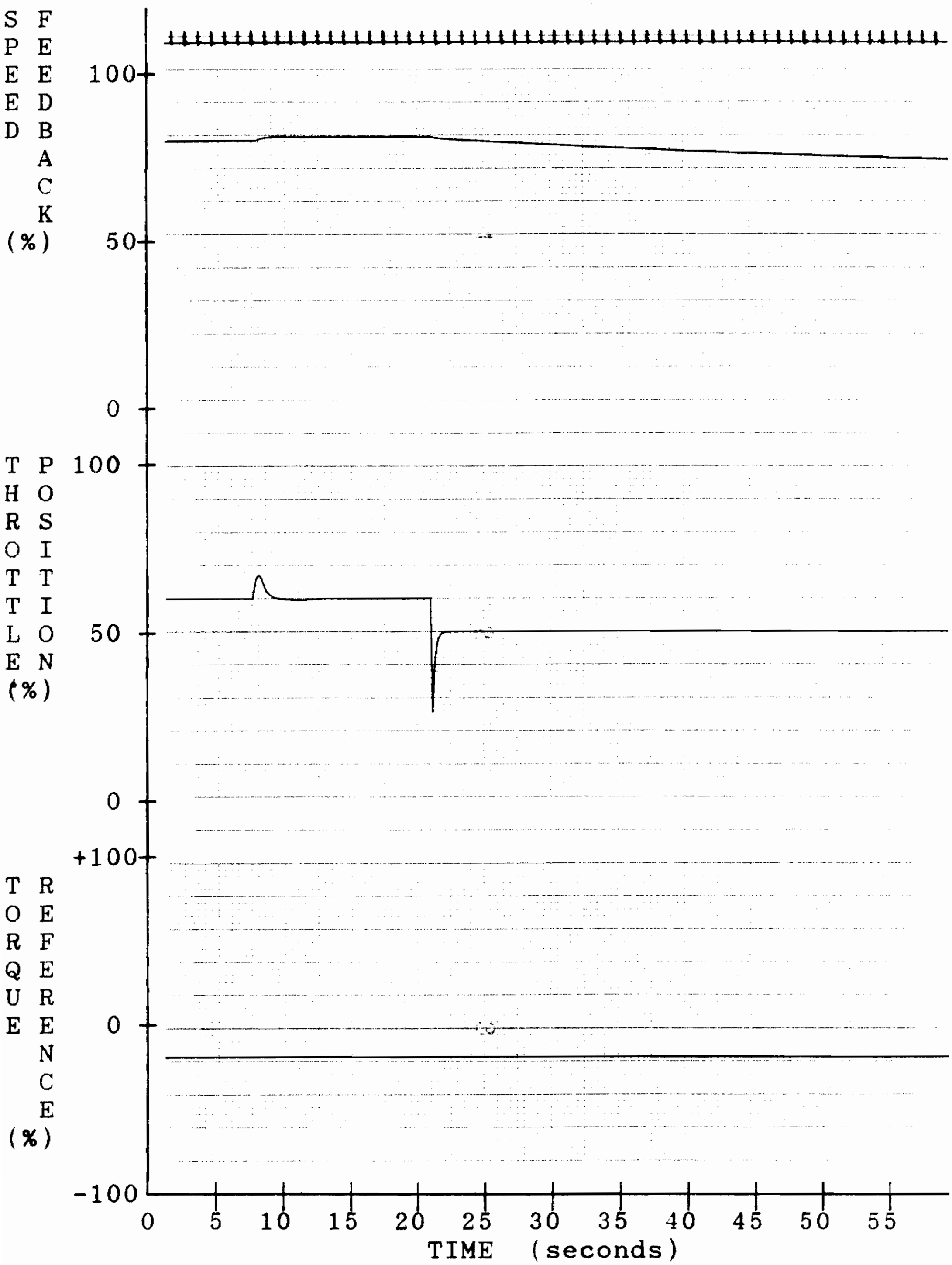

FIGURE C-6

PREDICTIVE CONTROL, NO INERTIA COMPENSATION

HIGH SPEED RANGE

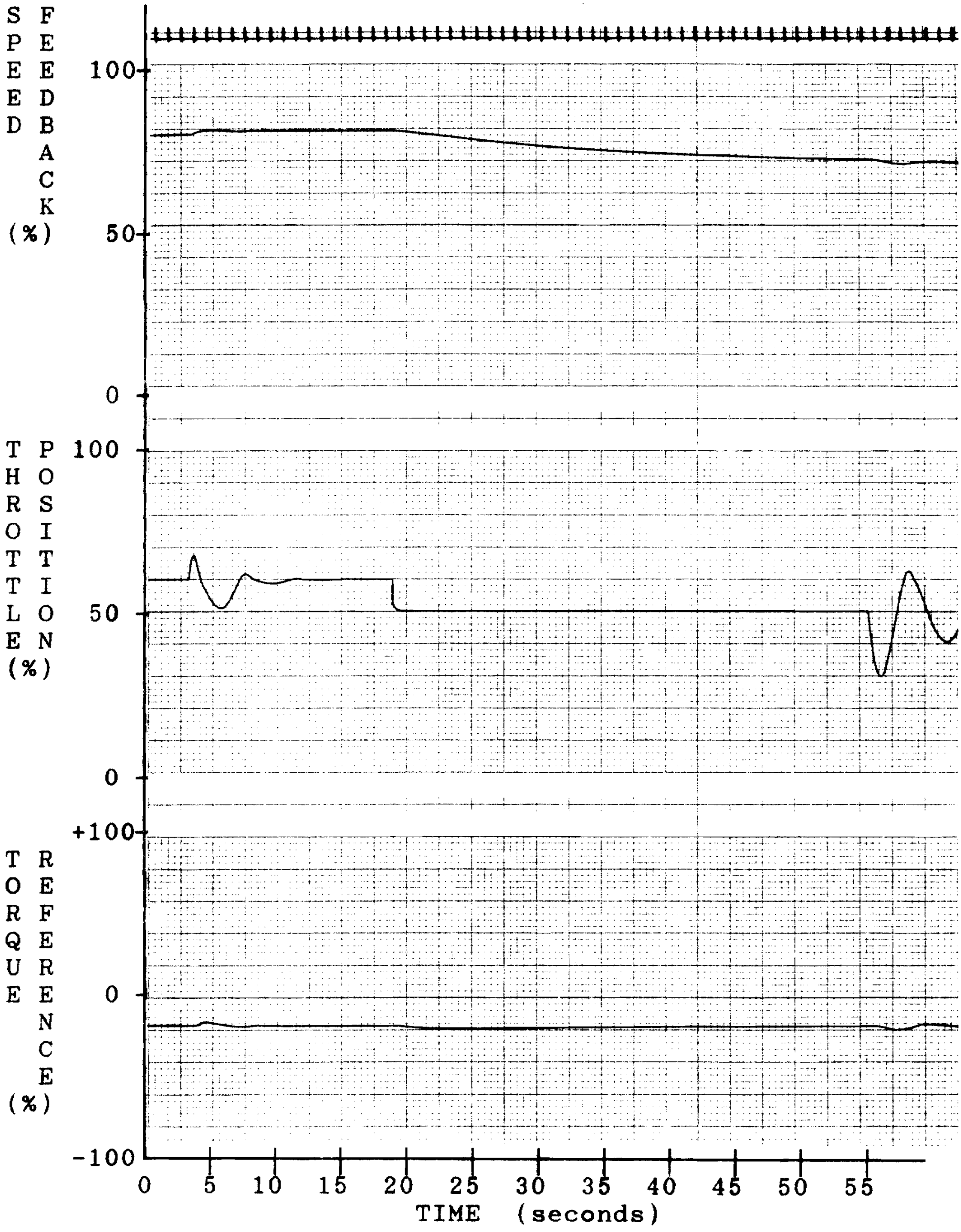

FIGURE C-7

<u>PREDICTIVE CONTROL, INERTIA COMPENSATION</u>

<u>HIGH SPEED RANGE</u>

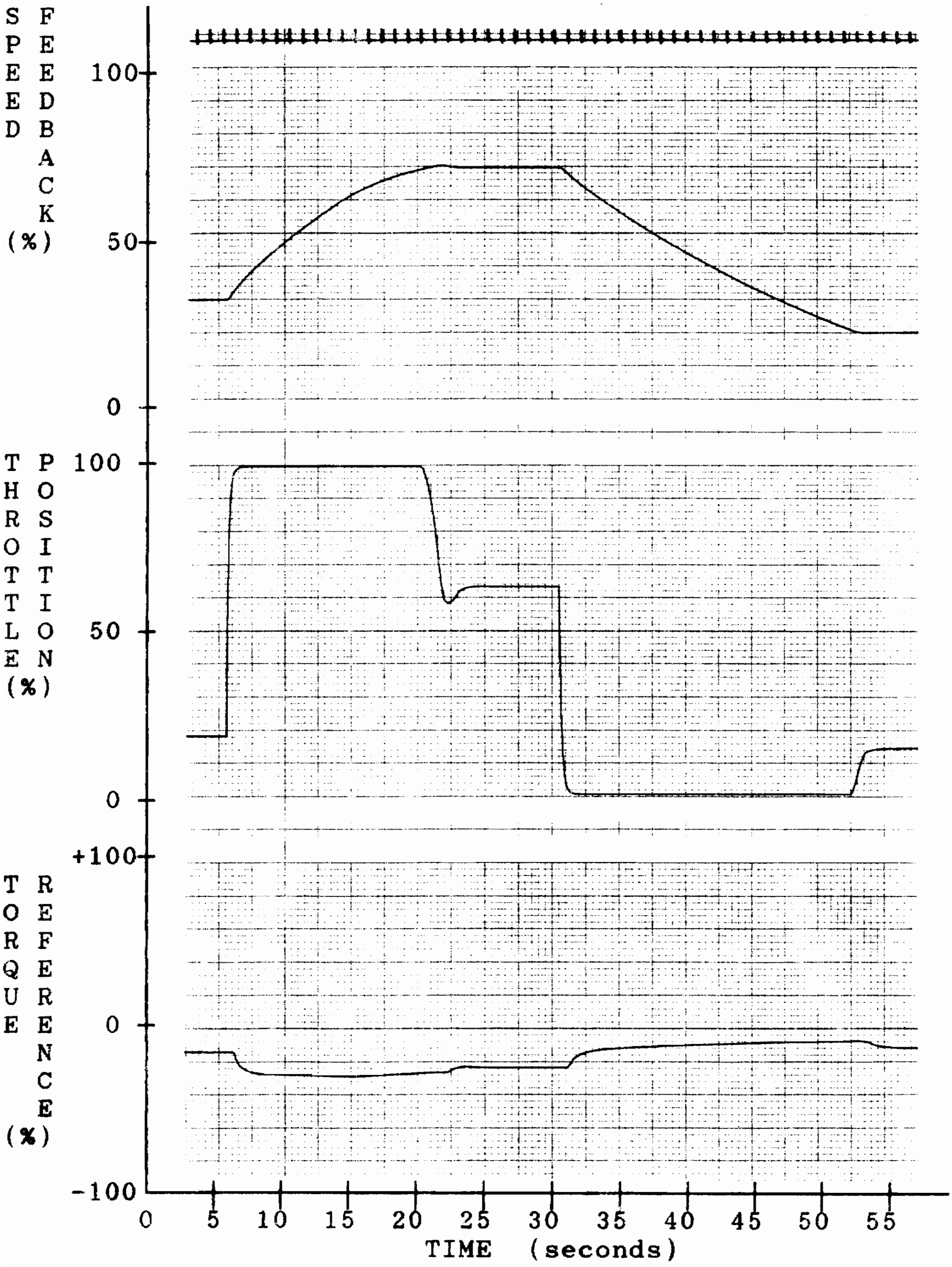

FIGURE C-8

SPEED REGULATOR, ROAD LOAD, GRADE (G) = .05

HIGH SPEED RANGE

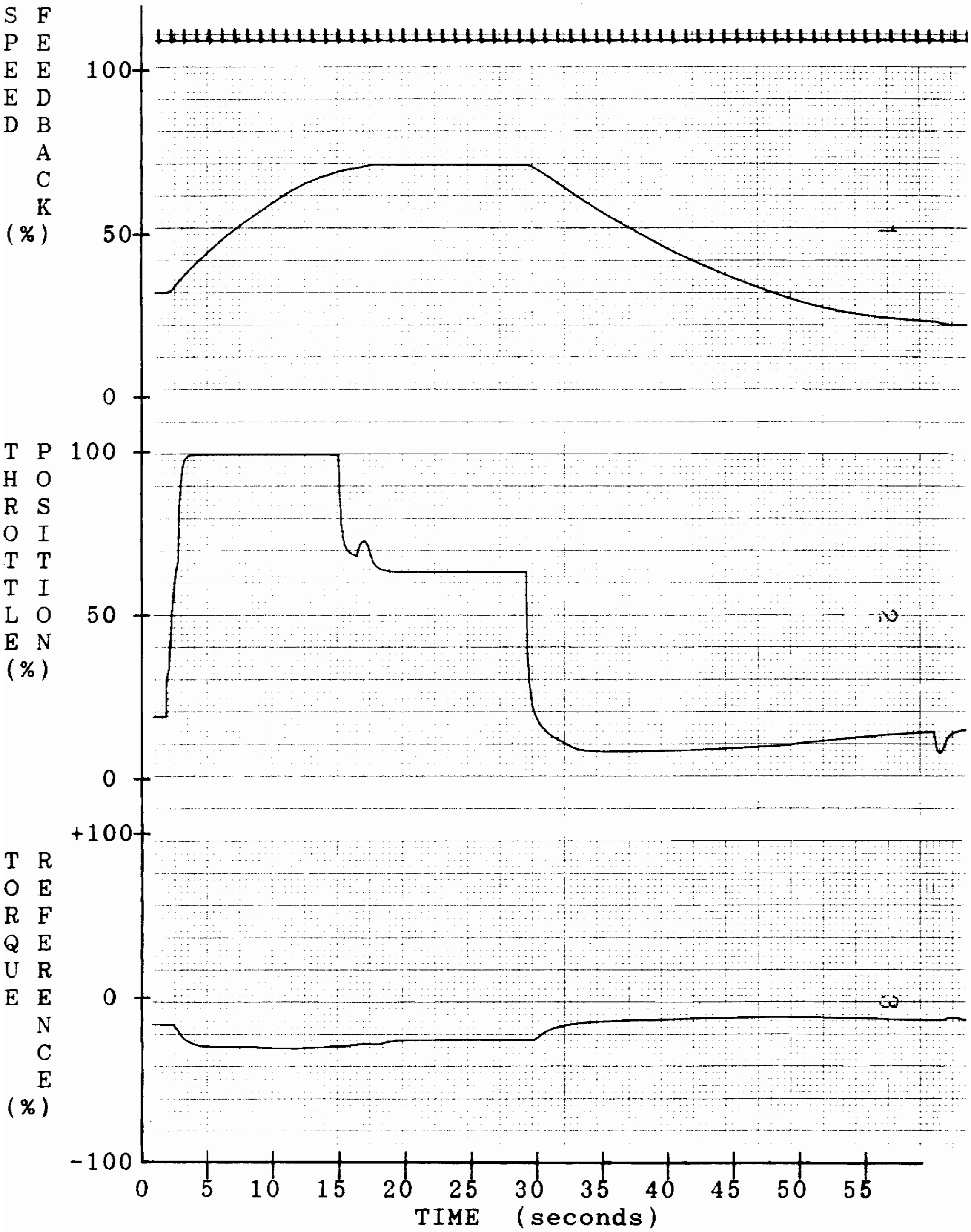

FIGURE C-9

PREDICTIVE CONTROL, ROAD LOAD, GRADE (G) = .05

HIGH SPEED RANGE

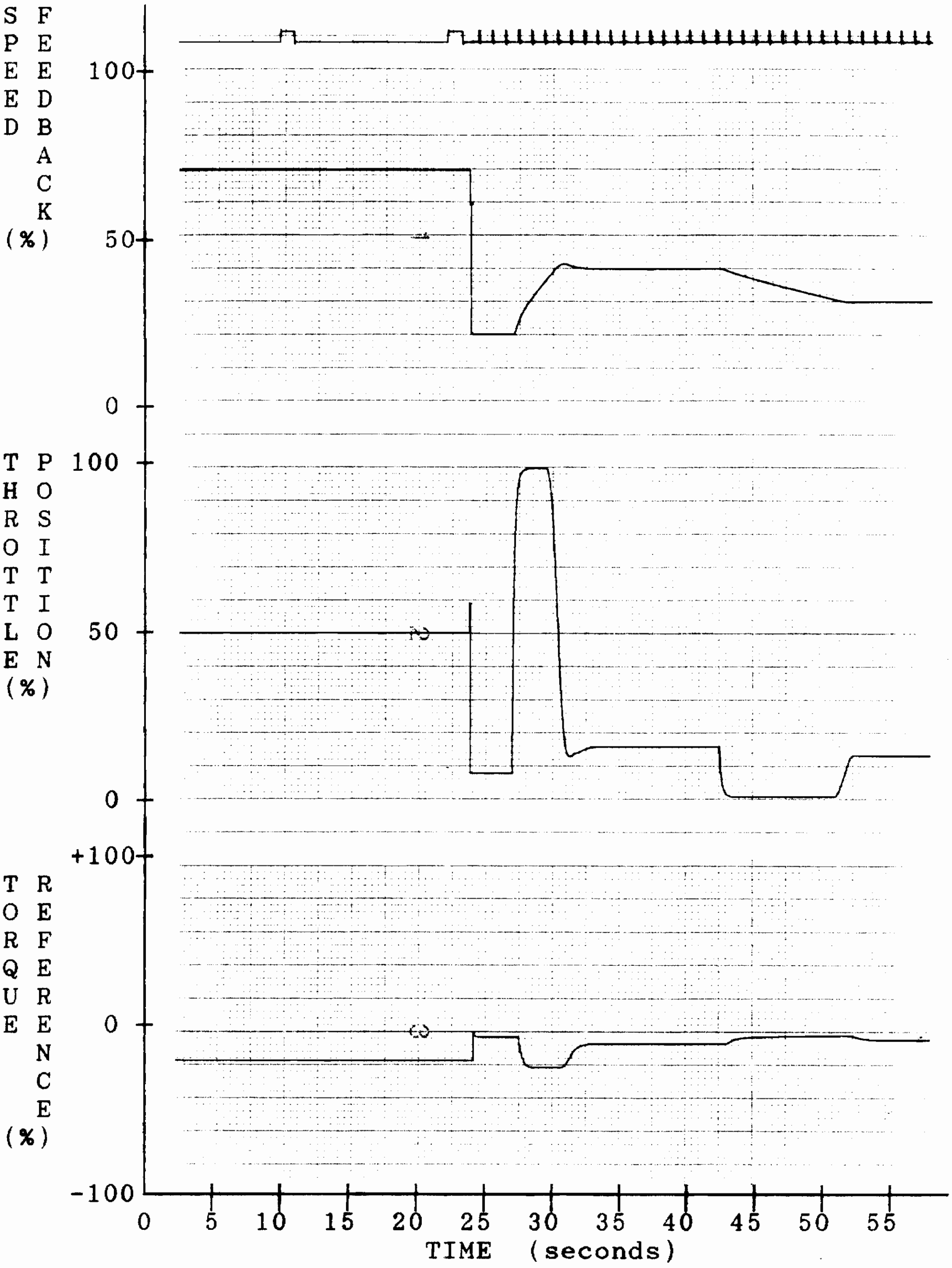

FIGURE C-10

SPEED REGULATOR, ROAD LOAD, GRADE (G) = .0

LOW SPEED RANGE

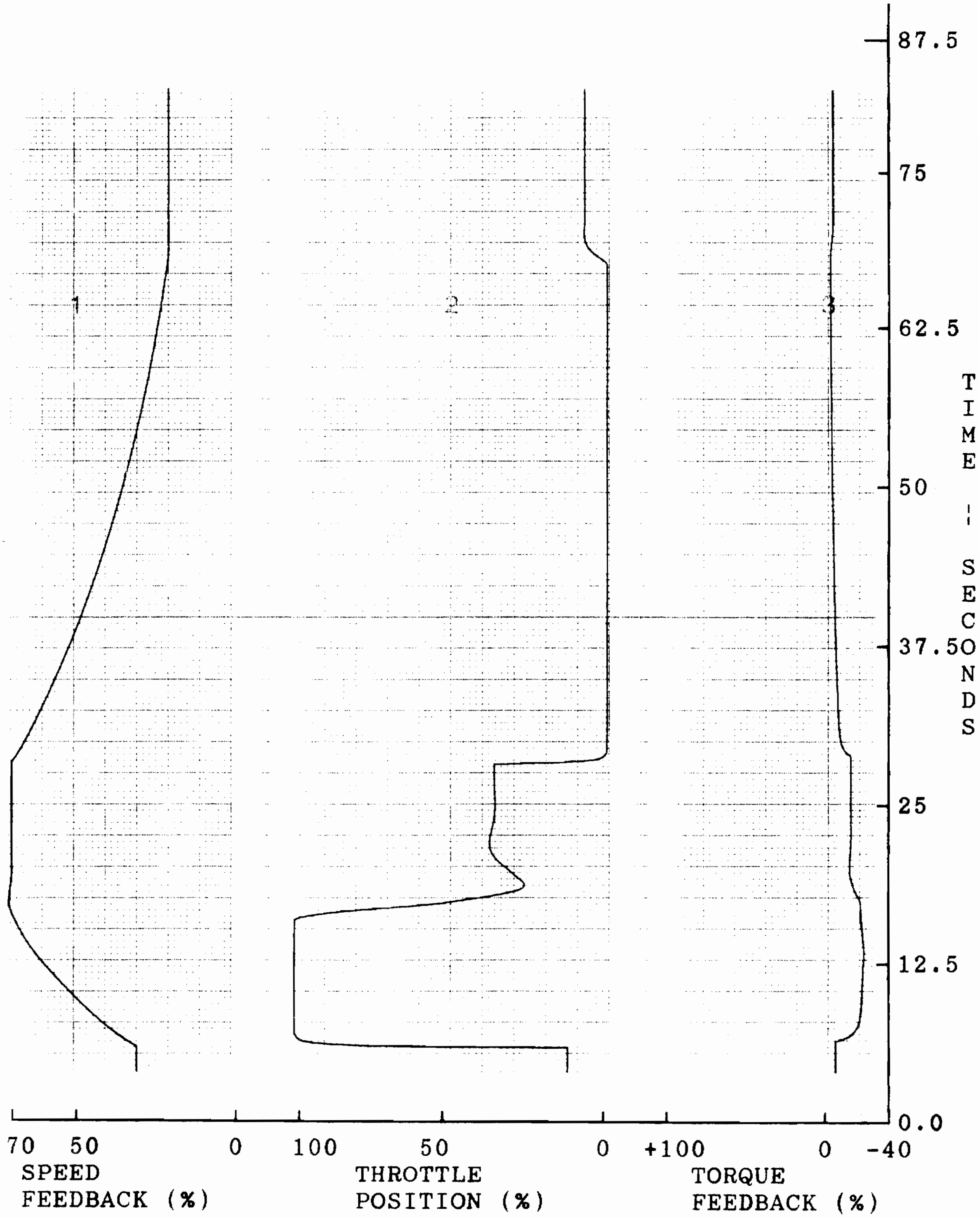

FIGURE C-11

SPEED REGULATOR, ROAD LOAD, GRADE (G) = 0

HIGH SPEED RANGE

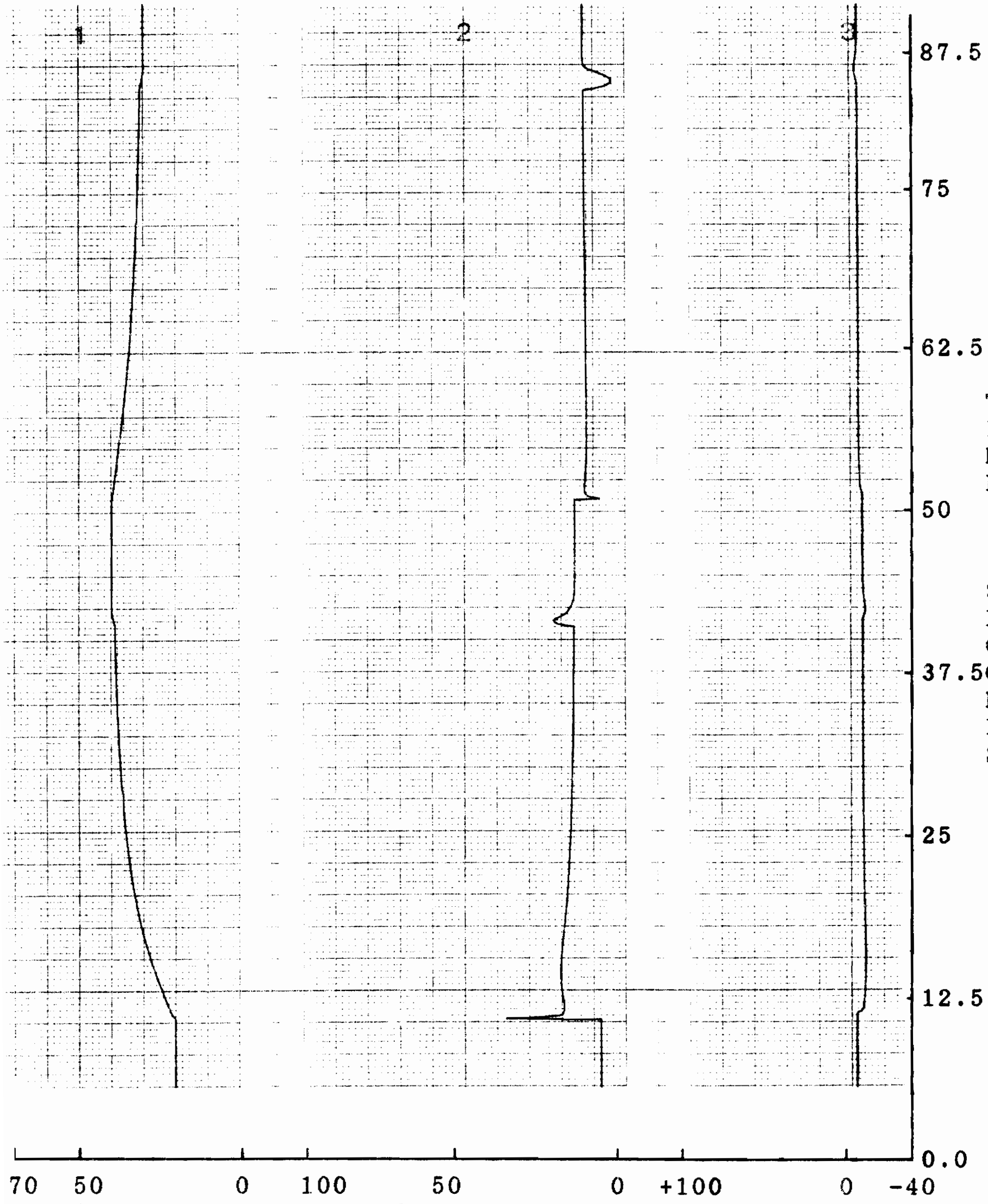

FIGURE C-12

PREDICTIVE CONTROL, ROAD LOAD, GRADE (G) = 0

LOW SPEED RANGE

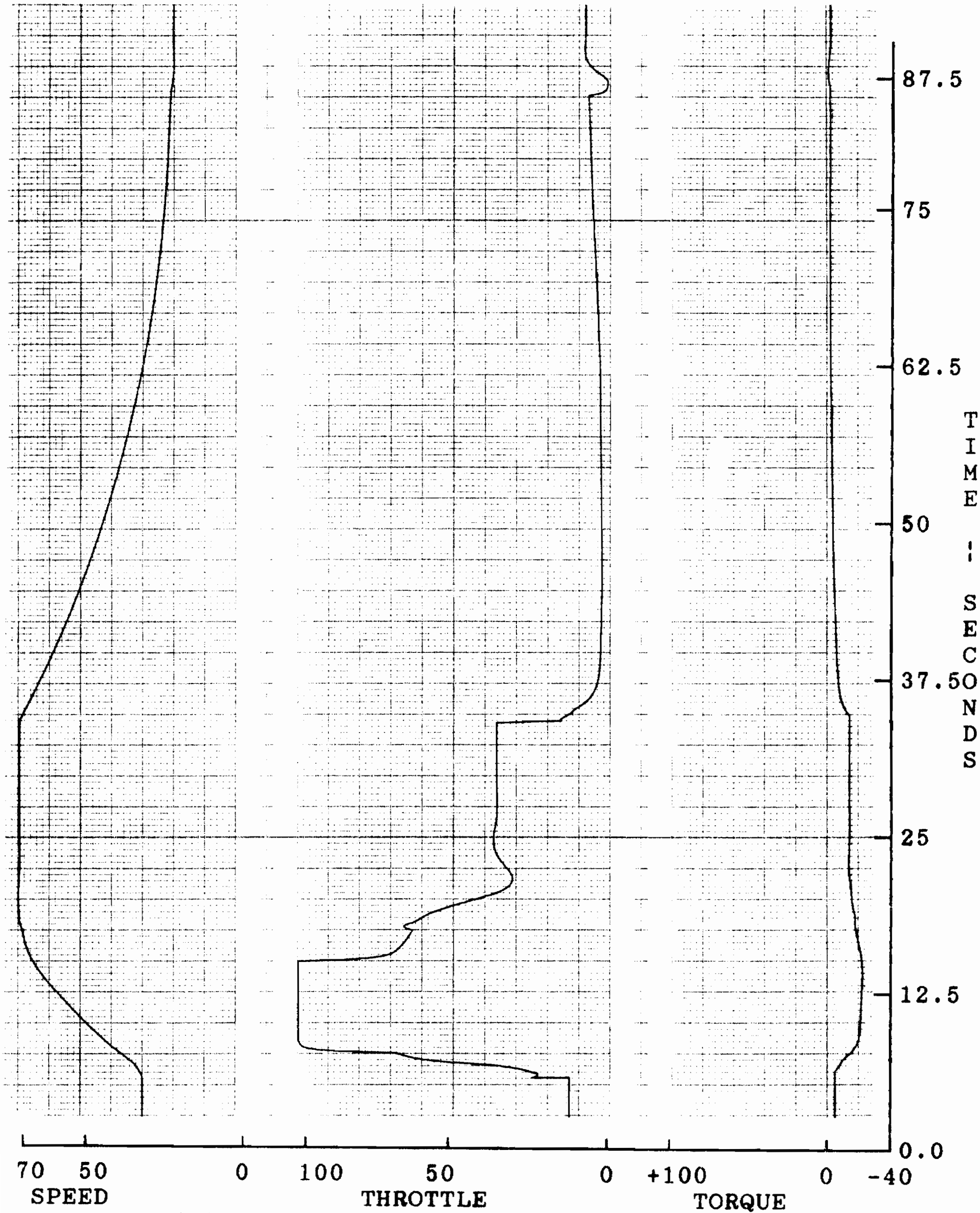

FIGURE C-13

PREDICTIVE CONTROL, ROAD LOAD, GRADE (G) = 0

HIGH SPEED RANGE

VITA

David Socky graduated from Ohio University at Athens, Ohio in 1973 with a bachelors degree in business administration. His first job was with General Electric at Louisville, Kentucky, working on GE's Manufacturing Management Program. This training program consisted of four different assignments over a two year period in various areas of manufacturing. The second year of training was at Circleville, Ohio with the lamp division.

After graduating from the Manufacturing Management Program, Socky took a position in Manufacturing Engineering at the General Electric Nela Park in Cleveland, Ohio. The work was related to the manufacture of high pressure sodium arc tubes.

In 1979, he took an educational leave of absence from General Electric and went back to school to obtain a bachelors degree in electrical engineering at Cleveland State University. After graduating in 1981, he moved to Roanoke, Virginia with a position of Control Engineer at General Electric's Drive System Division.

Up until this date, David Socky has worked on designing large control systems for various types of steel industry process lines. In 1983 he started work in General Electric's ABC engineering training program. Three years of work would lead to completion of the ABC program and a masters degree from VPI.

David Socky