AN AUTOMATIC SPEED CONTROL SYSTEM FOR AN AUTOMOBILE

A Thesis

Presented in Partial Fulfillment of the Requirements
for the Degree Master of Science

by

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ABSTRACT

The purpose of this study was to design, build, and test an automatic speed control system for an automobile. The results of full-scale highway tests of the designed system show that it could comfortably and efficiently maintain a desired speed of an automobile to within ±0.75 miles per hour over speeds ranging from 45 to 70 miles per hour in the presence of 10% road grades.

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CHAPTER I

INTRODUCTION

In the last 50 years the number of automobiles in the United States has increased from about 8 million to about 100 million, while the number of miles of roads has only increased 25 percent. Even with the building of modern multilane and interstate highways, the roadways are rapidly becoming choked with traffic.[1] In addition, surveys forecast that traffic will increase from 100 to 200 percent in the next 15 years.[2] The solution to the resulting problems cannot rely solely on the construction of more roads but must also include more efficient use of existing roads.

Considerable improvements in both highway capacity and highway safety could be accomplished by automation of the highways. Such automation must combine the desirable features of the private automobile--convenience, flexibility, comfort, and speed--with the advantages of public transportation systems--economy, safety, and relief from driving strain.[3]

Although a large number of possible highway automation systems that meet the above objectives have been suggested, the most frequently mentioned involves a combination of automated and nonautomated roads. Main highways would be automated while the smaller roadways would not.[4] Such a system would require an automobile capable of being both independently operated, as are today's automobiles, and automatically controlled. This system would consist of at least three integrated subsystems: one for longitudinal control, one for lateral control (steering), and one associated with manual control.[2]

Considerable research has been accomplished on such subsystems. For example, researchers at the Ohio State University have tested such subsystems in various highway situations at typical highway speeds.[4-6] Further, both the Ford Motor Company and General Motors Corporation are reportedly developing automatic systems for lateral and longitudinal control and vehicle spacing.[7,8]

For nearly every conceivable type of automated highway system, some method of longitudinal control for the automobile would be required. A complete longitudinal control system would control a vehicle's state--speed, acceleration, intervehicle spacing, etc.--with respect to the surrounding vehicles. The research reported here is concerned with one facet of this state--the speed and acceleration control of a single vehicle under quasi-steady state conditions. An automatic speed control unit, designed to enable an automobile to maintain a constant, preset speed regardless of the environment was designed, built, installed on a 1967 Buick GS-400, and tested under various driving conditions. The testing was conducted to show that the unit could maintain the automobile's preset velocity to within ±2 miles per hour under a variety of environmental disturbances and terrain variations and without excessive acceleration.

The speed control system discussed herein differs from other systems already in existence by the replacement of the mechanical sensing and control devices with electrical sensors and calculators. A brief discussion of a speed control system presently manufactured is contained in Appendix A.

A discussion of speed control theory is presented in Chapter II, the design and description of the speed control unit in Chapter III, and the testing and evaluations of the unit in Chapter IV.

CHAPTER II

SPEED CONTROL THEORY

A. Introduction

A thorough discussion of the speed control of an automobile would involve an understanding of the physics of vehicular motion and the effects of forces on the vehicle and its contents. However, the research presented here is concerned with maintaining a constant, preset speed in the presence of various environmental disturbances. The control of the resulting speed variations by the use of a relay servomechanism is discussed herein, together with a somewhat analogous driver-vehicle speed control system.

B. Driver-Vehicle Speed Control System

A block diagram of a driver-vehicle, speed-control system is shown in Fig. 1. The driver is shown as performing three primary functions--sensing, decision, and behavior.[7] His sensing of the instantaneous state of the vehicle would be accomplished aurally, kinesthetically, and visually.

In general, it would be expected that a driver would attempt to maintain a fixed speed by primarily relying on one

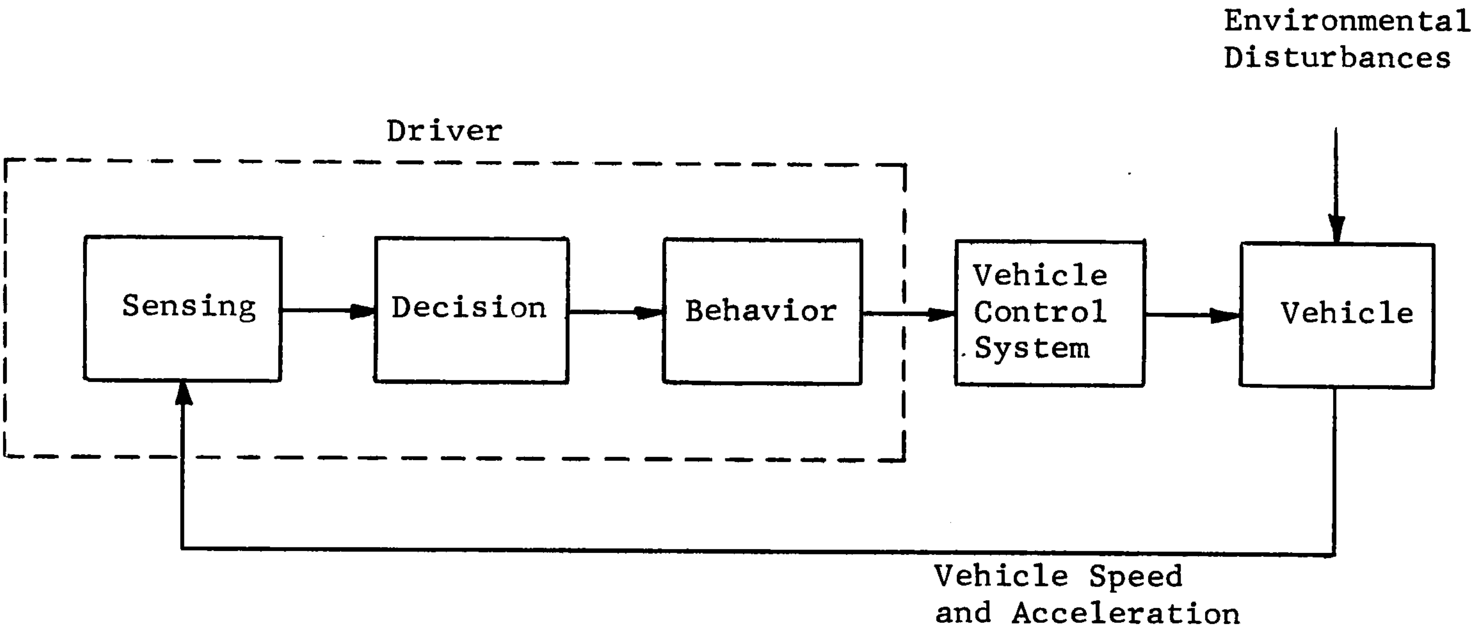

Fig. 1--Block diagram of the present driver-vehicle speed control system.

visual input--his indicated speed on the vehicle's speedometer. His decision would then be determined by the comparison of his observed velocity with the desired one. If the difference between the two were greater than desired, the driver would initiate a change to the system by his behavior. This behavior would be expressed in the form of mechanical energy that would change the position of the gas pedal and hence the state of the vehicle. Environmental disturbances such as changes in road grading or wind gusts influence the vehicle's performance and are reflected in changes in the vehicle's speed.

The behavior of a driver can probably be considered as somewhat analogous to that shown in Fig. 2. Here V_o represents the actual desired speed although speeds within the range CC' are also considered acceptable; therefore, no driver reaction would occur in this range. Lines BC and B'C' approximate the magnitude of the driver's reactions as a function of change in velocity.

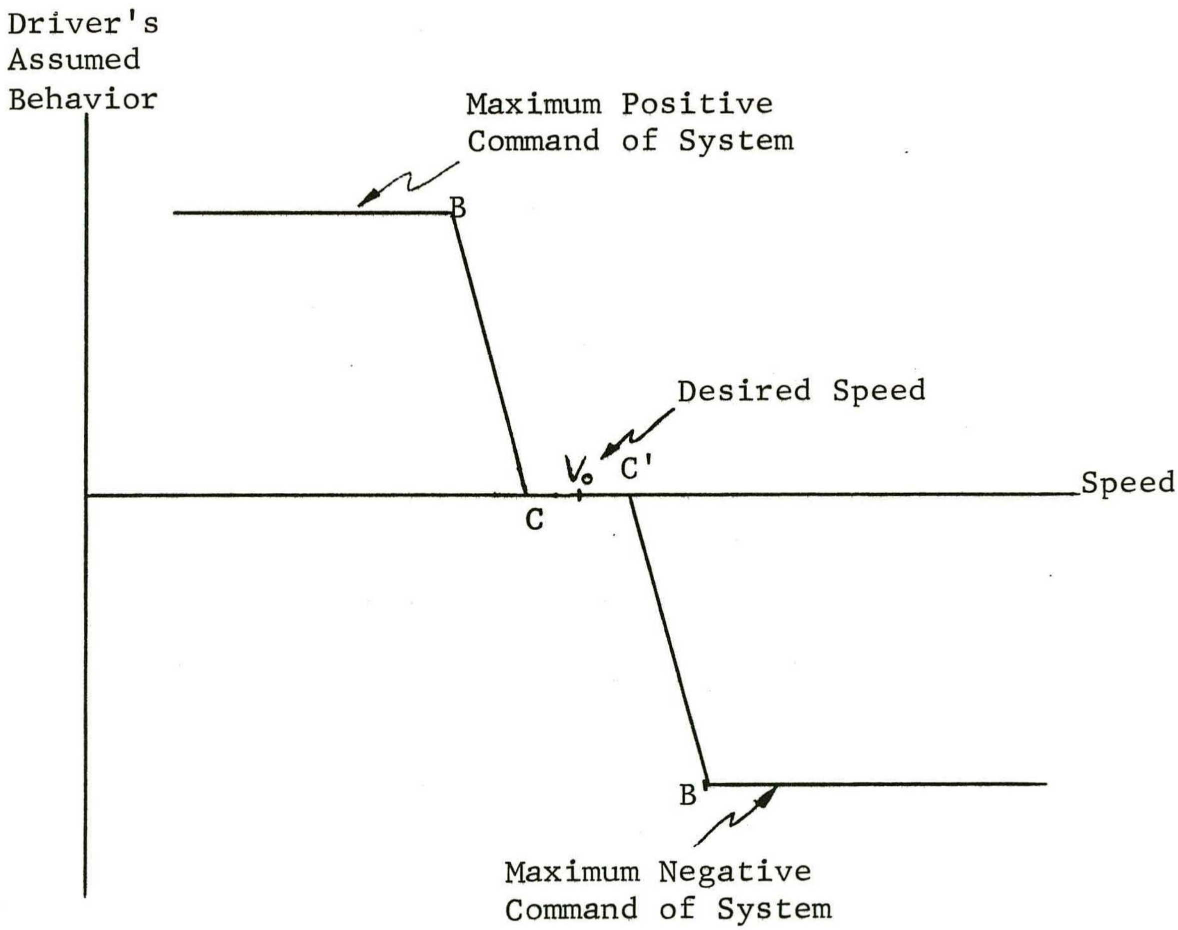

Fig. 2--Driver's behavior versus changes in speed.

To illustrate the driver's assumed reactions, suppose he were to notice that he were several miles per hour slower than desired as represented by point x in Fig. 3. By changing his commands to the system slightly in advance of the desired speed levels (point a), the velocity of the automobile would settle within the acceptable speed range as shown in Fig. 3.

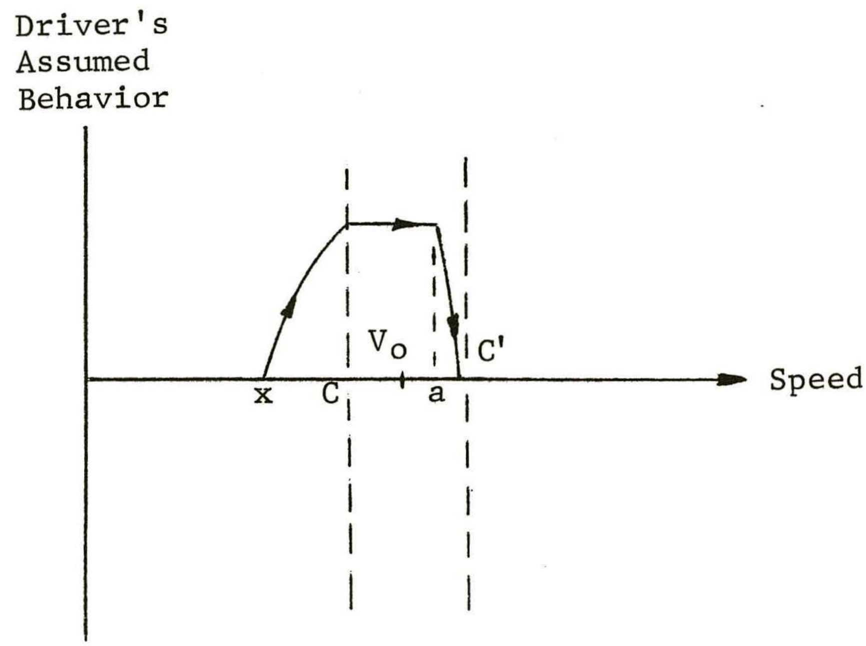

Fig. 3--Driver's correction of initial offset speed.

If the driver had waited to act until the vehicle's speed deviation was at C' (See Fig. 4), the vehicle's velocity would have probably settled somewhere above the acceptable velocity as shown in Fig. 4. The driver would then have to repeat the command process, this time with negative commands as shown in order to attempt to adjust the vehicle's velocity. This process of adjusting the speed could become cyclic with the vehicle's velocity oscillating about the desired velocity. In control terminology, this would correspond to a limit-cycle condition.

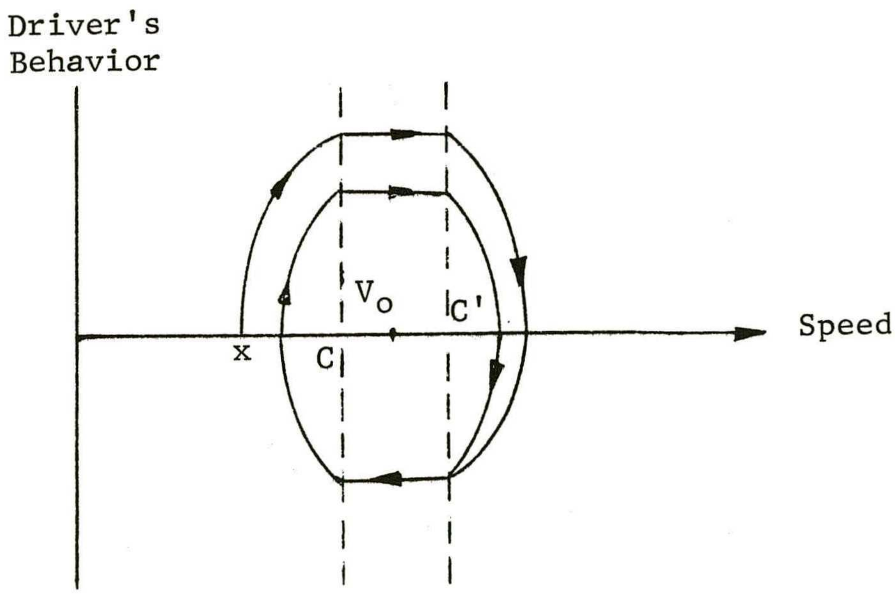

Fig. 4--Driver's attempted correction of initial offset speed.

The operating characteristics of relay servomechanisms are similar to the assumed behavior of the driver-vehicle control system outlined before. A system, therefore, based on the characteristics of a relay could conceivably be designed for a vehicle to be a partial substitute for the driver under certain situations, as in maintaining a constant speed. Advantages of such a system would include reduced driver fatigue, more accurate speed control, and safer vehicle operation since the driver could concentrate on other duties instead of controlling his speed. A discussion of relay servomechanisms follows.

C. Relay Servomechanisms

A simple relay servomechanism can be represented by the block diagram shown in Fig. 5. The error e activates the relay causing the contactor to assume one of the three positions +A, 0, -A, depending on the magnitude of e.

Typical input-output relationships of a relay are shown in Fig. 6. The time delay between the error voltage changes and the contactor's movement was considered negligible. Note the similarities of the relay's characteristics and the assumed driver behavior that was shown in Fig. 2.

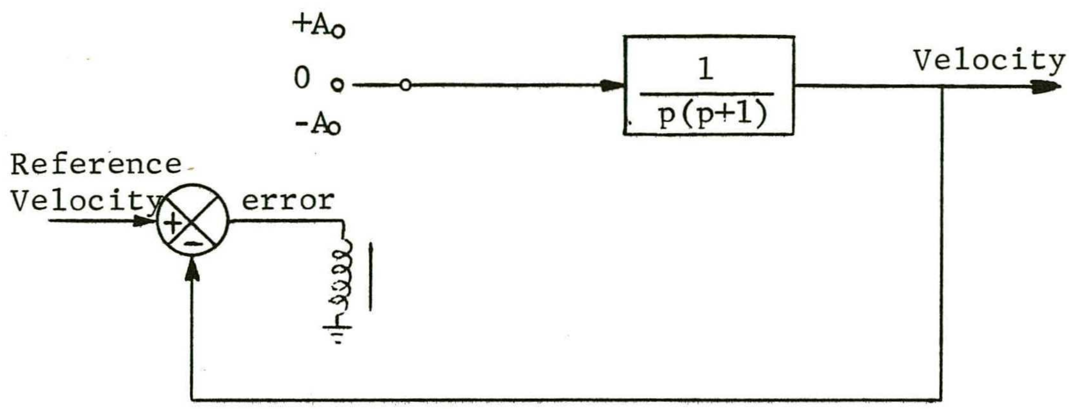

Fig. 5--Block diagram of a relay servomechanism.

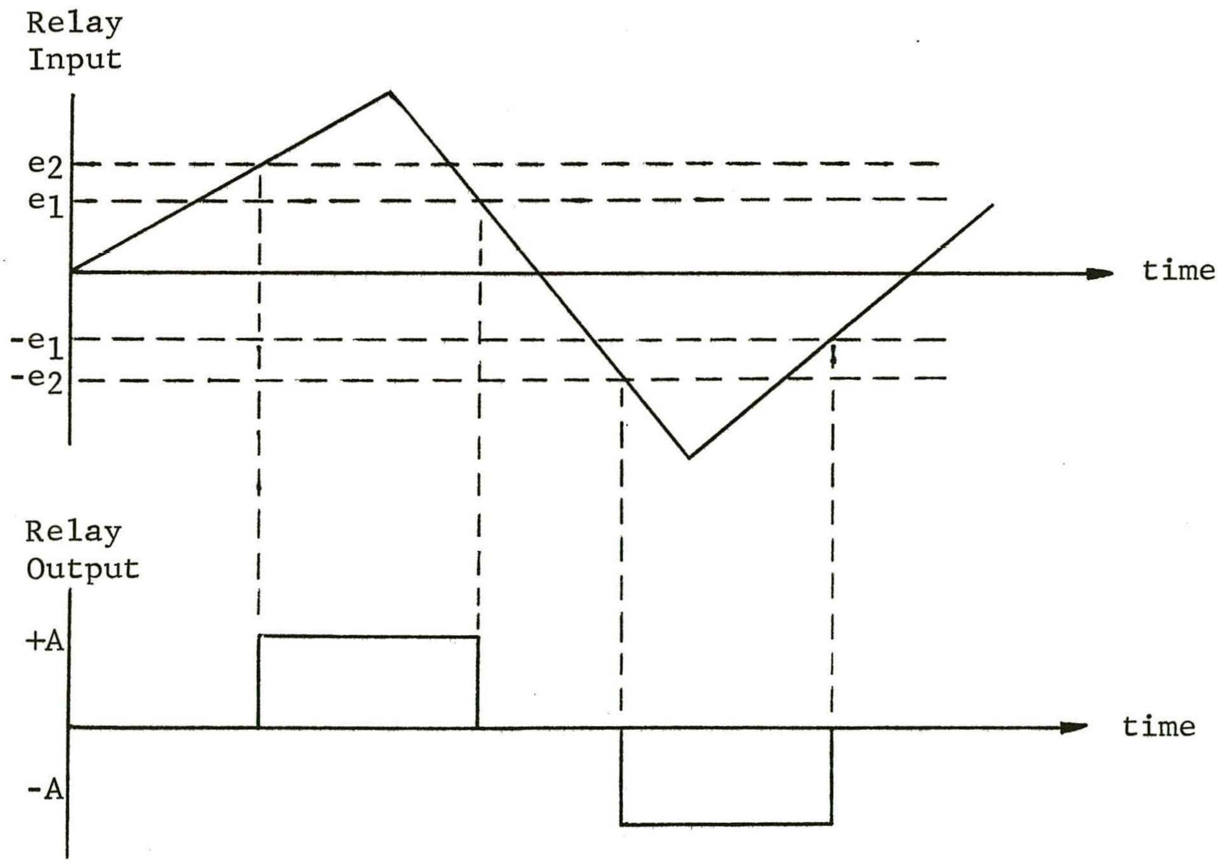

Fig. 6--Input-output relationship of a relay.

The performance of relay servomechanisms has been examined in detail by Cosgriff[9] using phase-plane analysis. By plotting e versus $\frac{de}{dt}$, he depicted a convenient approach to studying the behavior of a closed loop system containing a relay and excited by various initial conditions. A typical example of a phase-plane plot for a relay controlling a second-order linear system of the form $\frac{1}{p(p+1)}$ is shown in Fig. 7. The figure depicts a control system with a stable limit cycle.

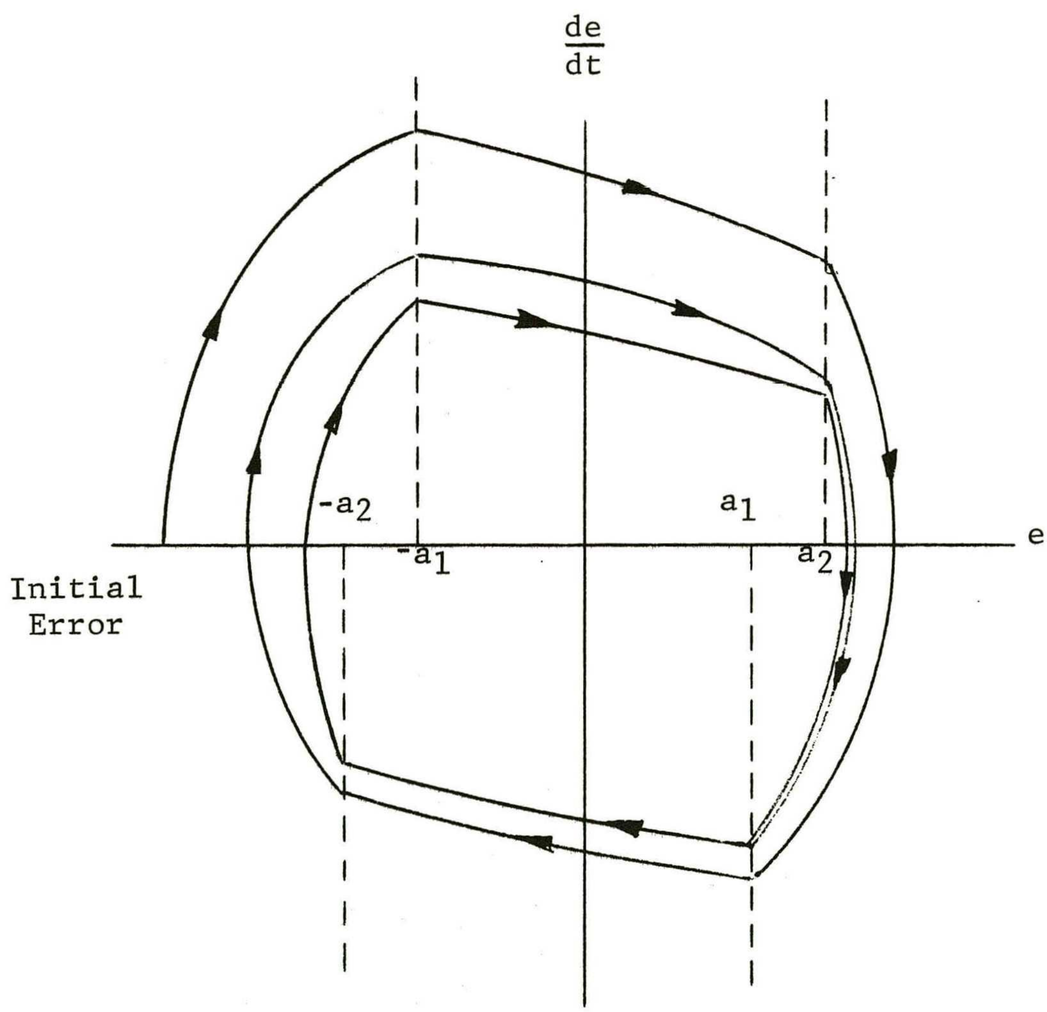

Fig. 7--Response of a relay servomechanism to an initial condition excitation.

The limit cycle can sometimes be eliminated by modifying the system so that a signal of the form $\frac{(p + a)}{(p + b)}e$ $(a<b)$ activates the relay as shown in Fig. 8. This modification changes the slope boundaries of the relay from those shown in Fig. 7 to those of Fig. 9 resulting in few or no overshoots and no limit cycle.

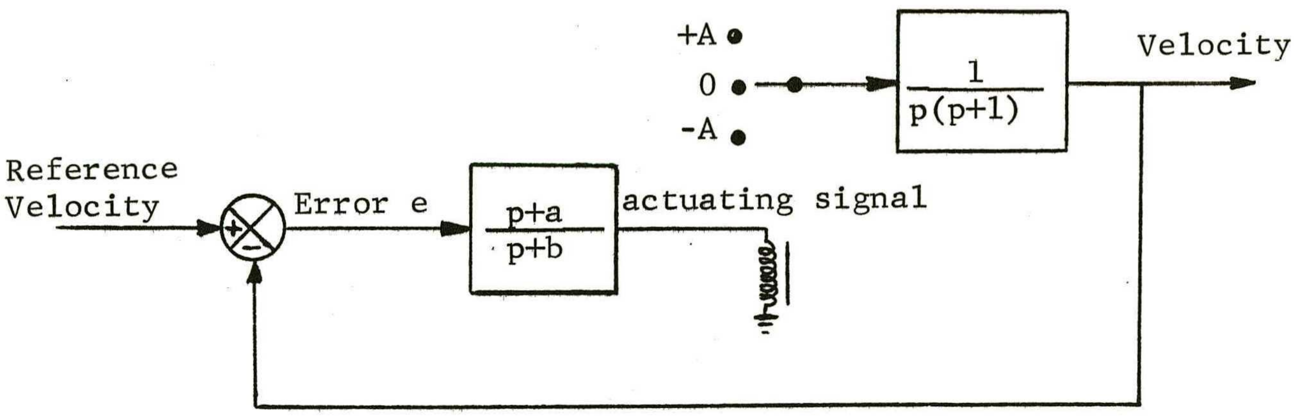

Fig. 8--Block diagram of a relay servomechanism with lead compensator.

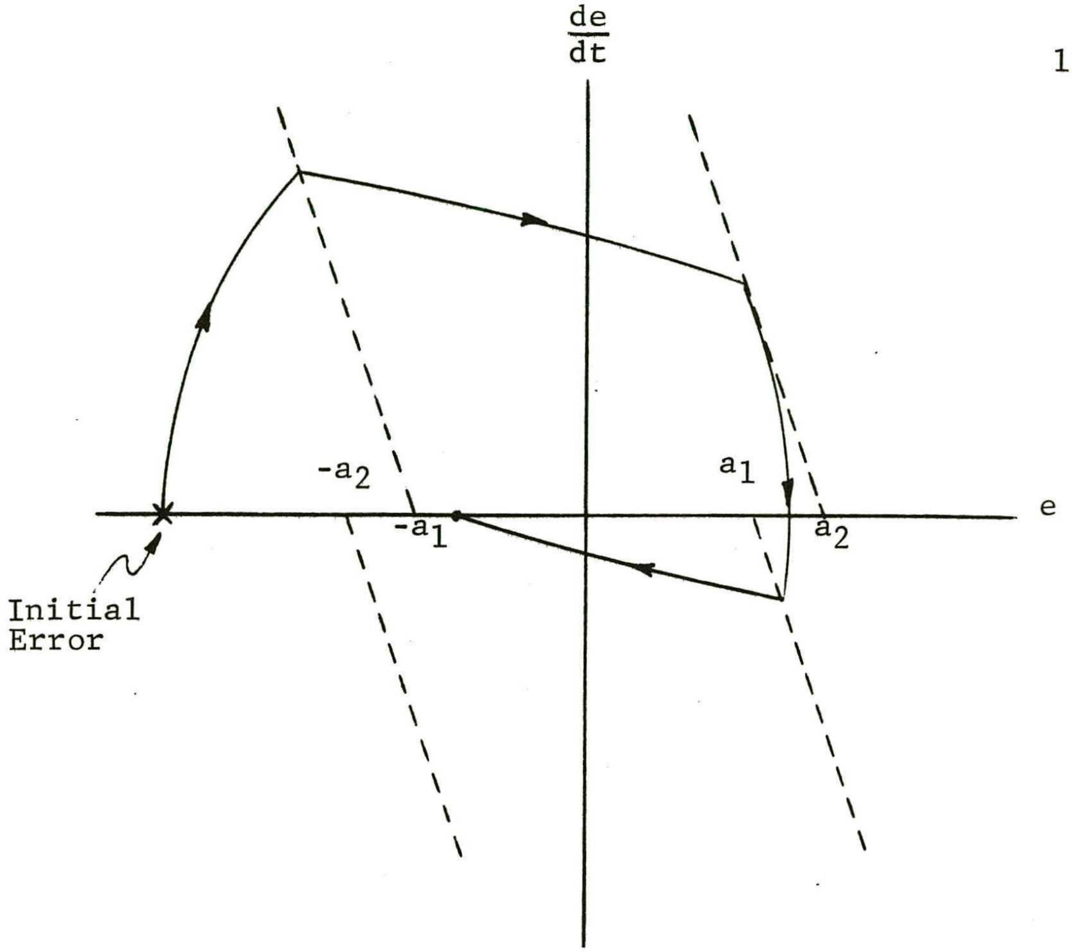

Fig. 9--Phase-plane diagram of a lead compensated relay servomechanism with an initial speed error.

A system based on the principles of relay servomechanisms could then be used as a partial substitute for the driver under certain situations. A discussion of a system designed on such principles is presented in the next chapter.

CHAPTER III

DESIGN AND DESCRIPTION OF THE SPEED CONTROL UNIT

A. Introduction

A basic block diagram of a speed control system for an automobile based on the discussion presented in the previous chapter is shown in Fig. 10. The purpose of the system is to maintain a constant, preset velocity of an automobile to within ±2 miles per hour in the presence of various environmental disturbances.

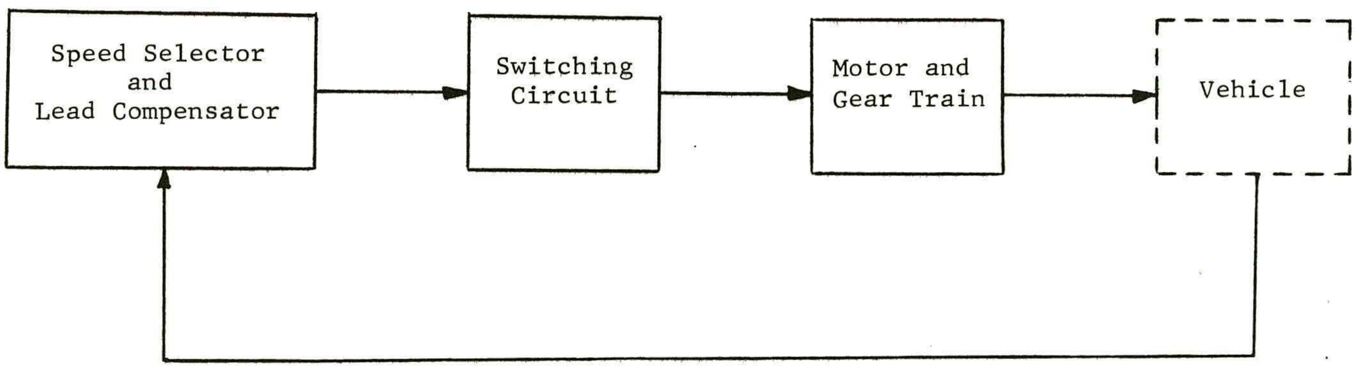

Fig. 10--Block diagram of a speed control system for an automobile.

Other requirements of the system, based on the safety, comfort, and convenience of the passengers in the automobile, are:

1. The driver must be able to quickly disengage the system from control of the automobile.
2. Normal operation of the automobile should not be hindered when the system is not in use.
3. Vehicle acceleration should be kept at a minimum for the comfort of the passengers.

The basic subsystems of the speed control unit--motor and gear train, switching circuit, speed selector and lead compensator circuit--are described in the following paragraphs.

B. Motor and Gear Train

The purpose of the motor and gear train is to move the throttle linkage to control the speed of the automobile. Considerable difficulty was encountered in the selection of the motor and gear train due to the following stringent requirements:

1. The motor had to operated on the existing 12-volt negative ground power supply of the automobile.
2. The motor direction had to be reversible.
3. The motor had to have a high starting torque since full load would be applied at starting.

4. The output speed of the motor and gear train should be between 2 and 4 revolutions per minute.

5. The gear train must be releasable from the throttle linkage when required.

The motor selected (See Fig. 11) was a 12-volt, series d. c. motor with two field windings wound in opposite directions, thus enabling one to easily reverse the motor's direction. A wiring diagram of the motor is shown in Fig. 12. The series motor was chosen because of its high starting torque and available gear train that operated at approximately 3 revolutions per minute. An electromagnetic clutch was added

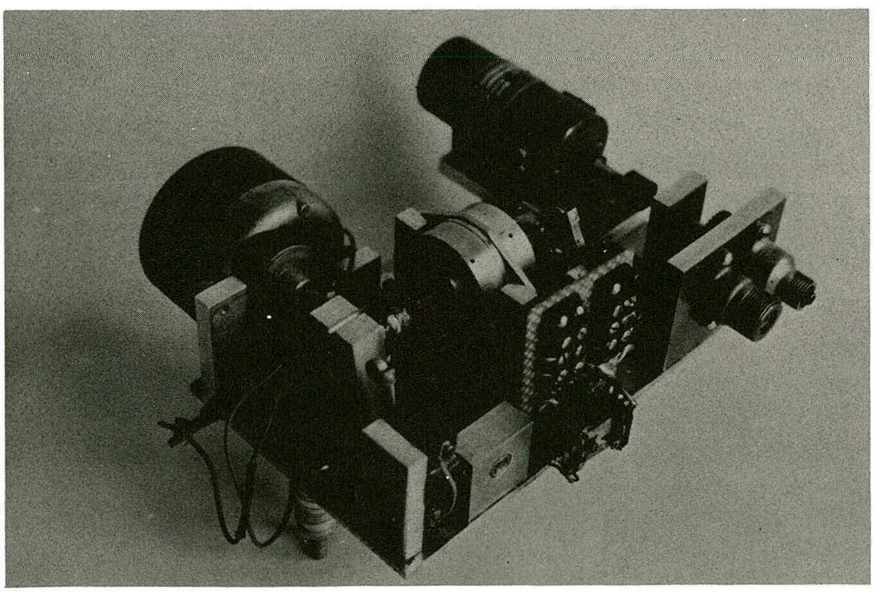

Fig. 11--Series d. c. motor, gear train, and clutch assembly.

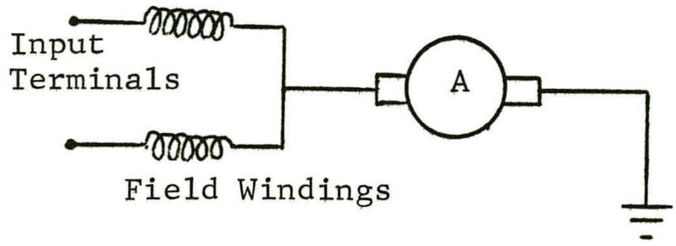

Fig. 12--Wiring diagram of the d. c. motor.

between the output of the gear train and the linkage to the throttle so that the motor and gear train could be engaged or disengaged as needed from the throttle linkage.

The motor and gear train were mounted as shown in Figs. 13 and 14 in the left front of the automobile because of space limitations in the engine compartment and heat given off by the engine. The linkage between the gear train and the throttle was arranged as shown in Fig. 14 to allow rocking of the automobile's engine without causing mechanical interference in the operation of the speed control unit.

C. Switching Circuit

A circuit diagram of the switching circuit is shown in Fig. 15. This circuit was constructed to meet the following requirements:

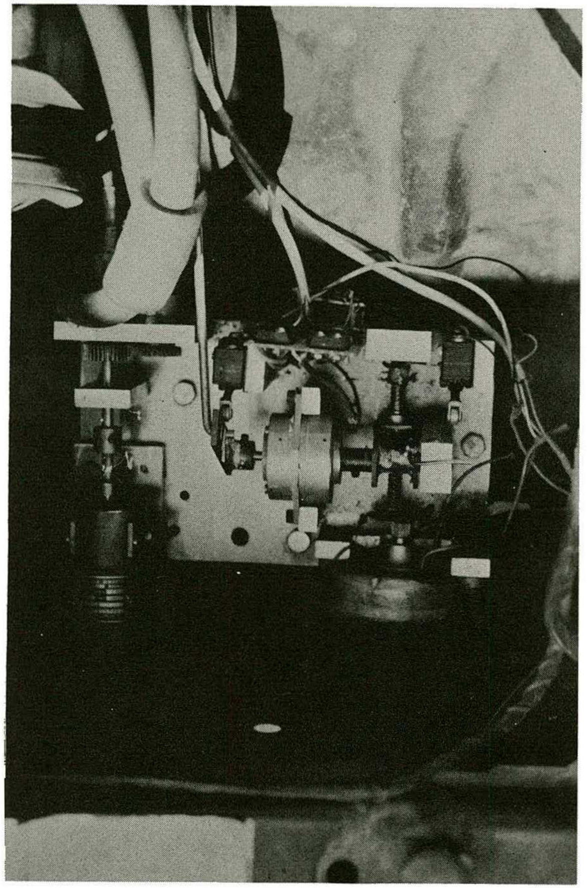

Fig. 13--Motor and gear train mounted in the left front of the engine compartment.

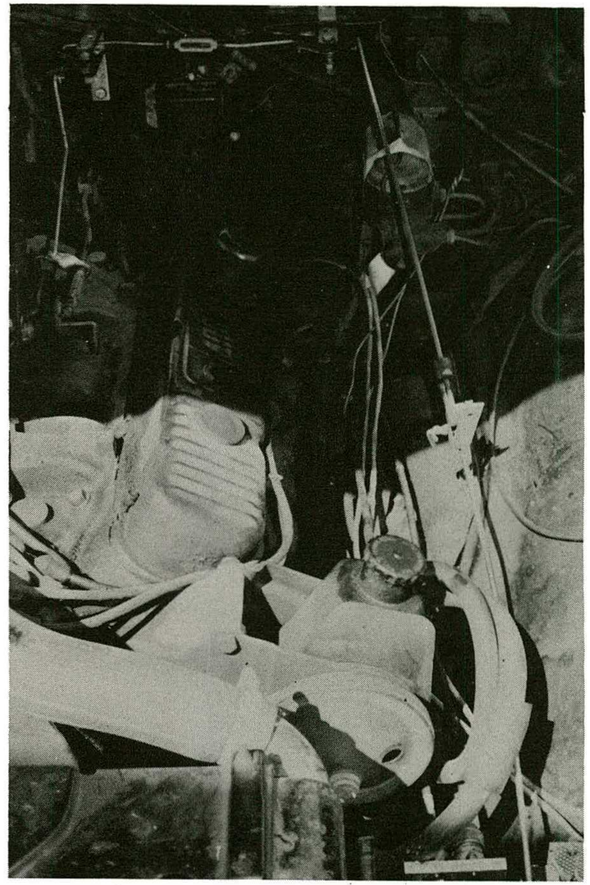

Fig. 14--View from front of automobile showing the motor and gear train and the linkage run to the throttle.

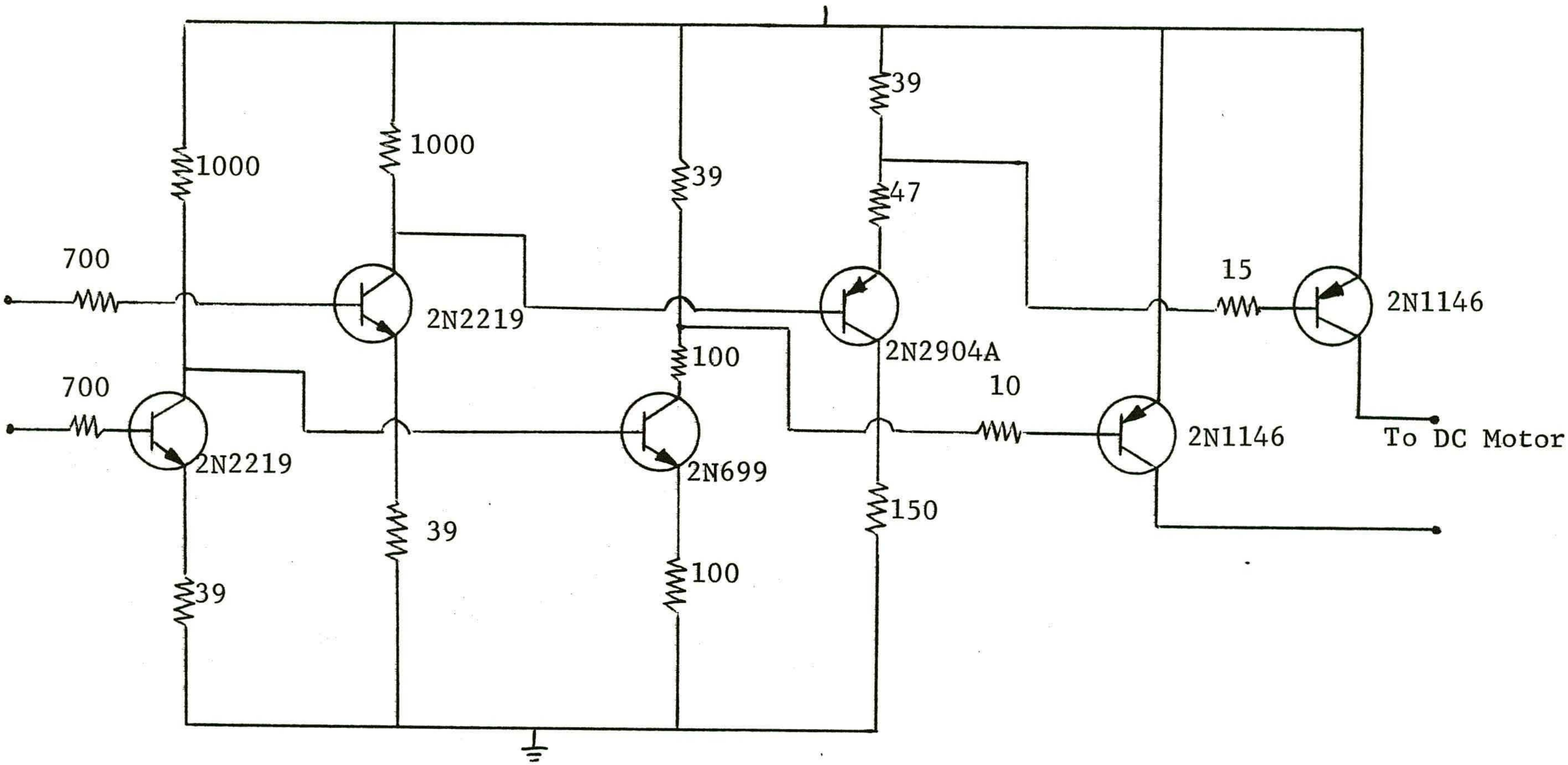

Fig. 15--Switching circuit diagram.

1. The circuit had to be able to detect a change of 3% in the input voltage (See Appendix B).
2. When the input voltage changed 3%, the output voltage and current had to be sufficient to drive the motor and gear train combination so as to achieve a suitably rapid response.
3. The circuit had to be compatible with the 12-volt negative ground power supply of the automobile.

The circuit design was patterned after a relay's characteristics, i. e., a small variation of input voltage would produce a large variation of output voltage. High-power transistors were used instead of a relay because of their faster switching times and no associated hysteresis which is characteristic of relays. The final circuit was tested and results showed that variations of ±0.02 volts about a nominal 1-volt input saturated the two output power transistors used to drive the motor and gear train (See Fig. 16). The resulting 2% sensitivity was within the desired requirement of 3%, meaning that the speed should be controllable to within ±1.3 miles per hour.

D. Speed Selector and Lead-Compensator Circuit

The combination speed selector and lead-compensator

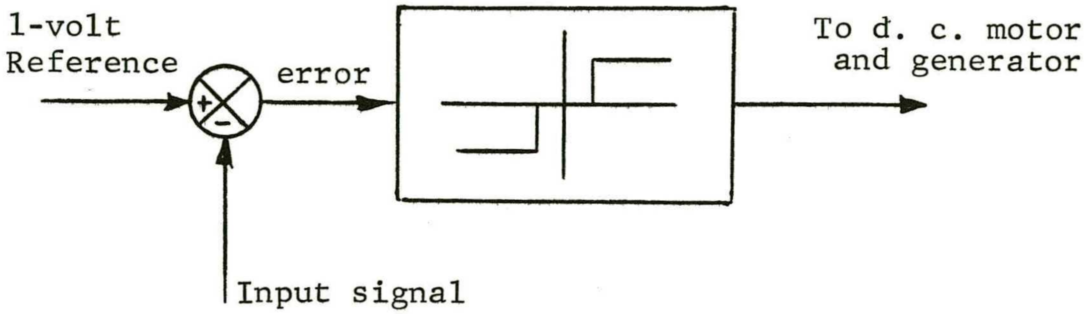

Fig. 16--Block diagram of switching circuit.

circuit is shown in Fig. 17. The circuit was designed to provide the input signal, consisting of the 1-volt d. c. voltage and the error signal, to the switching circuit and to eliminate any possible limit cycle conditions (See Fig. 18). Any deviation from that 1-volt input was considered an error and would activate the switching circuit.

The generator in Fig. 17 is also shown in Fig. 11 attached to the same chassis as the motor and gear train. The method of driving the generator by the speedometer cable was chosen because the gears and cables needed were readily available and no major modifications were required to the automobile. Use of the speedometer was maintained with a separate gear and cable taken off the cable running the generator.

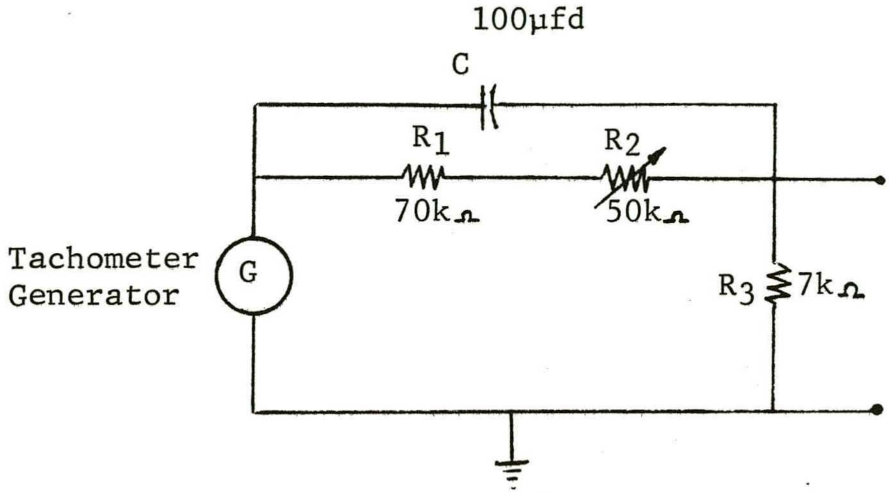

Fig. 17--Speed selector and lead-compensator circuit diagram.

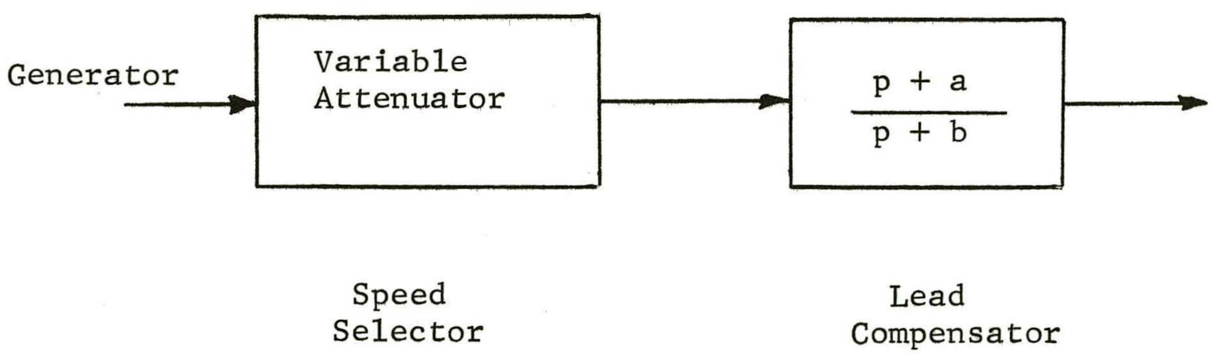

Fig. 18--Block diagram of the speed selector and lead-compensator circuit.

The output voltage of the generator was 22 volts at 60 miles per hour. The choice of operating speed was then determined by the value of R_2, the 50kΩ variable resistor in Fig. 17, needed to give a 1-volt input to the switching circuit. Increasing the value of the resistor produced greater attenuation in the circuit thus requiring a larger output voltage from the generator. Consequently, a higher corresponding speed was maintained; decreasing the value of the resistor likewise decreased the speed.

The circuit shown in Fig. 17 also functioned as the required lead compensator to eliminate overshoot and oscillation problems inherent in relay-type switching circuits. The transfer function of the lead compensator is given as

$$\frac{p + a}{p + b} \qquad a<b$$

where

$$a = \frac{1}{(R_1+R_2)C}$$

$$b = \frac{1}{(R_1+R_2)C} + \frac{1}{R_3C}$$

substituting the values of R_1, R_2, and R_3 into the above equations yields the following depending on the value of R_2

$$0.0835<a<0.143$$

$$1.51<b<1.57$$

The values of a and b were chosen after preliminary testing of the circuit and automobile without the capacitor C shown in Fig. 17. This means that the compensator was not used and the speed of the automobile was found to oscillate about ±2 miles per hour at a rate of approximately 0.2 Hz (Experimental data taken later and recorded during the performance tests of the system are given in Chapter IV.). The value of a was then chosen as 0.1 Hz and b as 1.5 Hz, thereby insuring adequate lead compensation at the oscillating frequency.

The large attenuation produced by this circuit reduced the output-voltage sensitivity due to variations in speed; thus an amplifying circuit (See Fig. 19) was added to regain the needed sensitivity.

E. Final Circuit

The final circuit of the speed control unit is shown in Fig. 20. The circuit was constructed, packaged in an aluminum chassis, and mounted inside the automobile as shown in Fig. 21. The large number of variable resistors required to set up the circuit necessitated mounting some components outside the aluminum chassis.

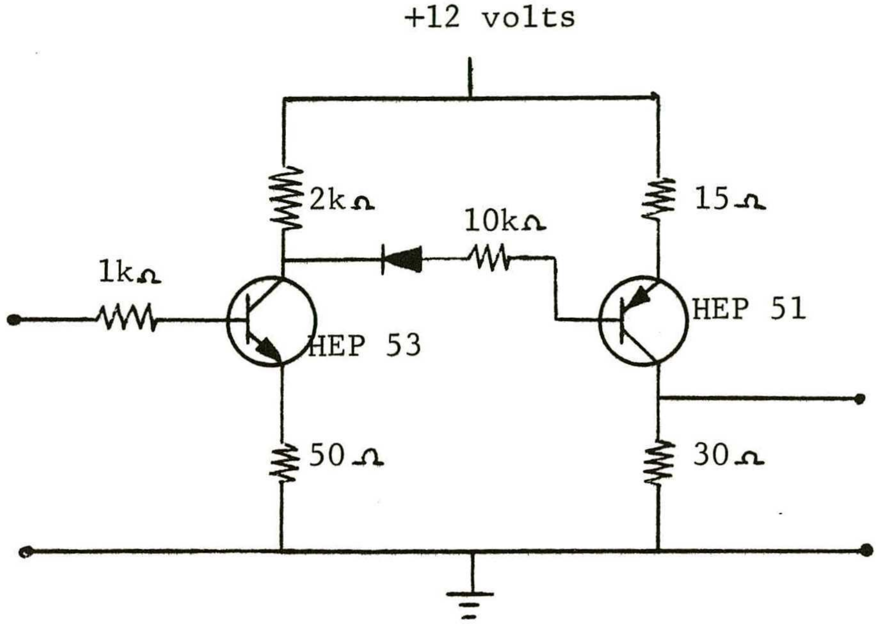

Fig. 19 --Amplifying circuit diagram.

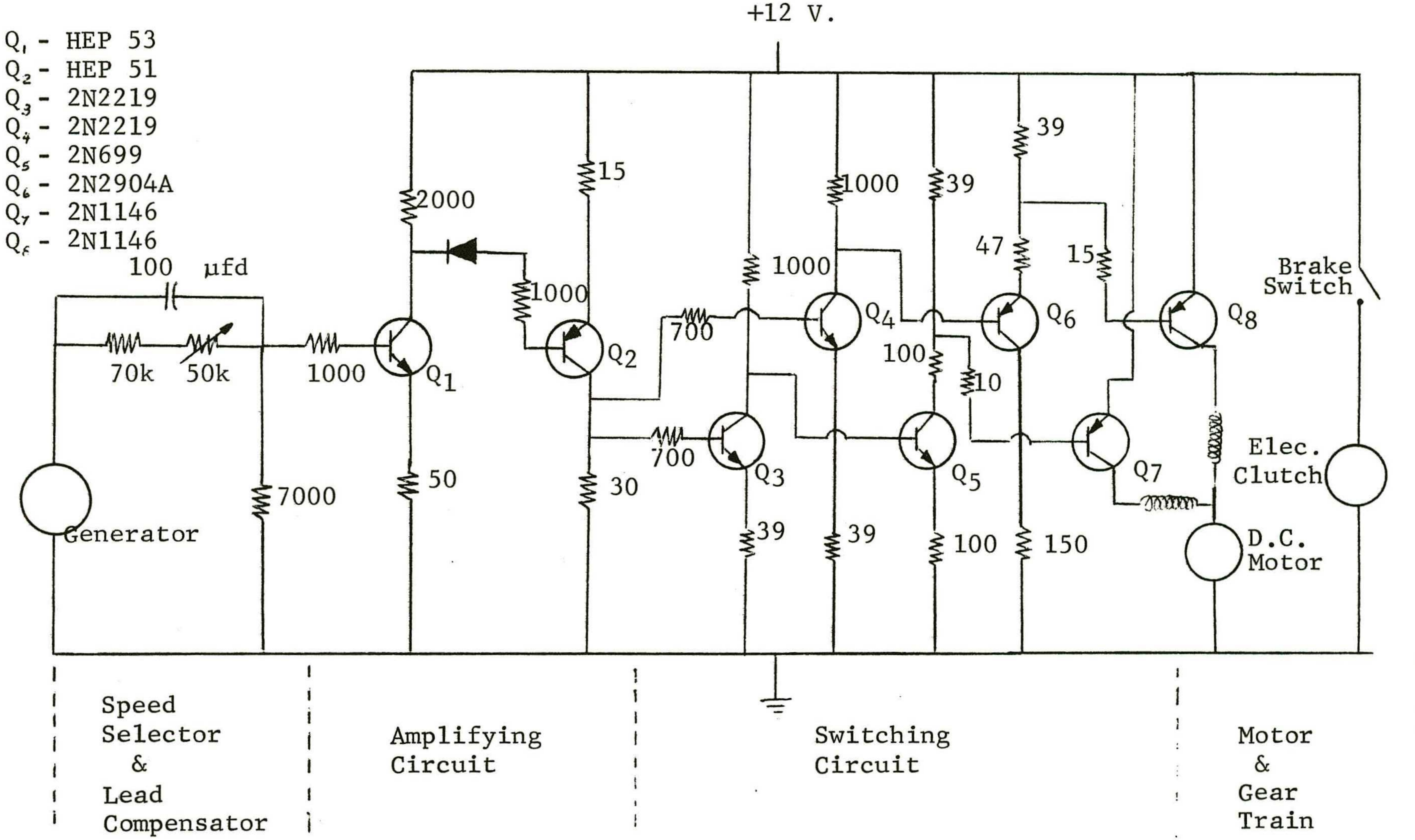

Fig. 20--Circuit diagram of the speed control unit.

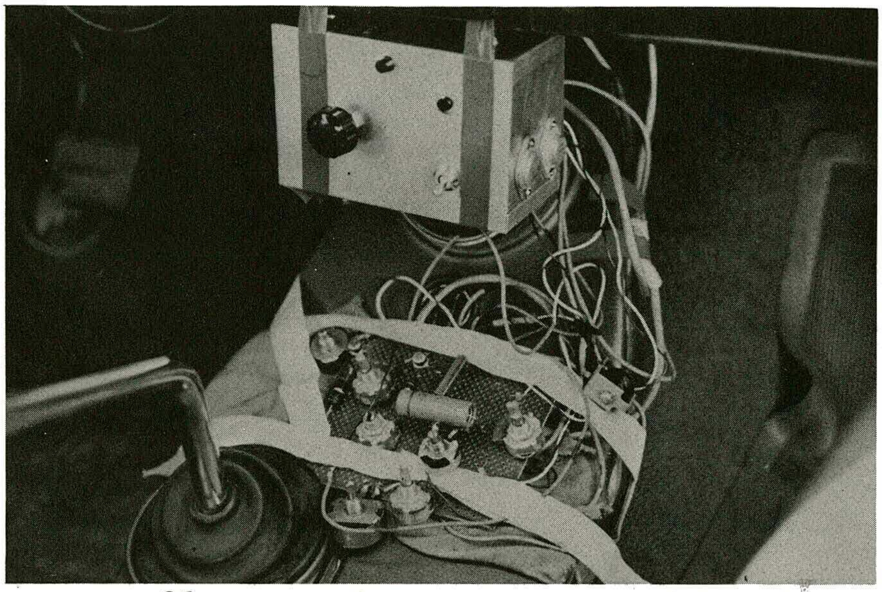

Fig. 21--Control circuit mounted inside the automobile.

CHAPTER IV

TESTING AND EVALUATION

A. Introduction

The testing and evaluation of the speed control unit is described in this chapter. The speed control unit described in the previous chapter was installed in a test automobile and the results of the tests recorded. The objectives of the tests are described first.

B. Test Objectives

The three objectives of the tests were:

1. To determine if the speed control unit could maintain the vehicle's speed to within ±2 miles per hour.
2. To determine the response of the automobile if the preset speed was changed while the speed control unit was in operation.
3. To obtain enough information about the switching characteristics of the circuit to enable a phase-plane diagram to be drawn.

C. Description of the Tests

The tests were conducted along a portion of Interstate

Highway 70 between Springfield, Ohio, and the Indiana state border. This section of roadway was selected because it offered the wide variety of road grading (ranging from level to about 10%) essential for the tests. Tests involving wind gusts were not made as wind gusts higher than 5 or 10 miles per hour did not occur when the recorder was available for testing purposes.

The recording-equipment configuration is shown in Fig. 22. Originally the test plan called for the recording of three voltages simultaneously--the generator voltage and the two outputs of the power transistors used to drive the motor. These three voltages were to be used to determine the switching characteristics of the system as well as for monitoring the speed of the automobile. However, the strip-chart recorder available for vehicular use only had two recording channels so complete switching data could not be gathered.

Noise, probably generated by the automobile's generator and voltage regulator, also greatly complicated the problem of determining the switching characteristics of the circuit. The recordings shown in Fig. 23 show the effects that noise had on the output of the power transistors used to drive the d. c. motor. The predominant 13 Hz rate shown was probably generated by the generator or voltage regulator of

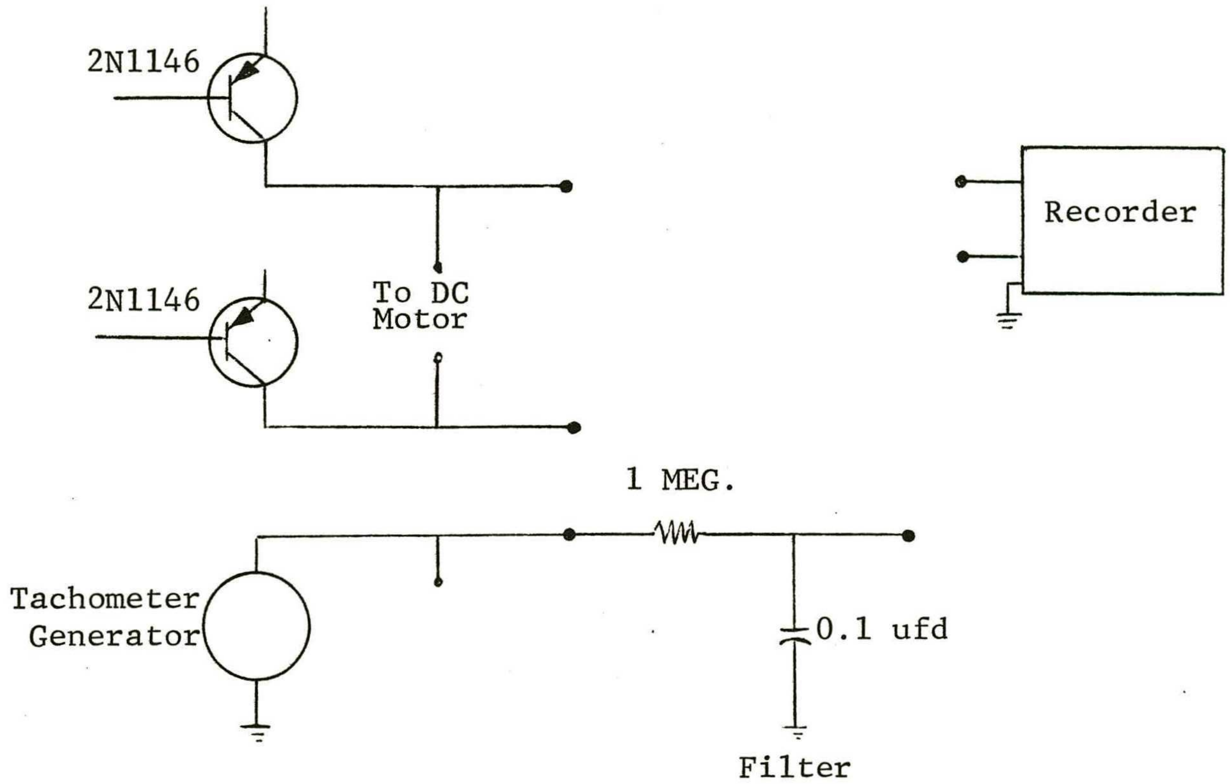

Fig. 22--Recording equipment configuration.

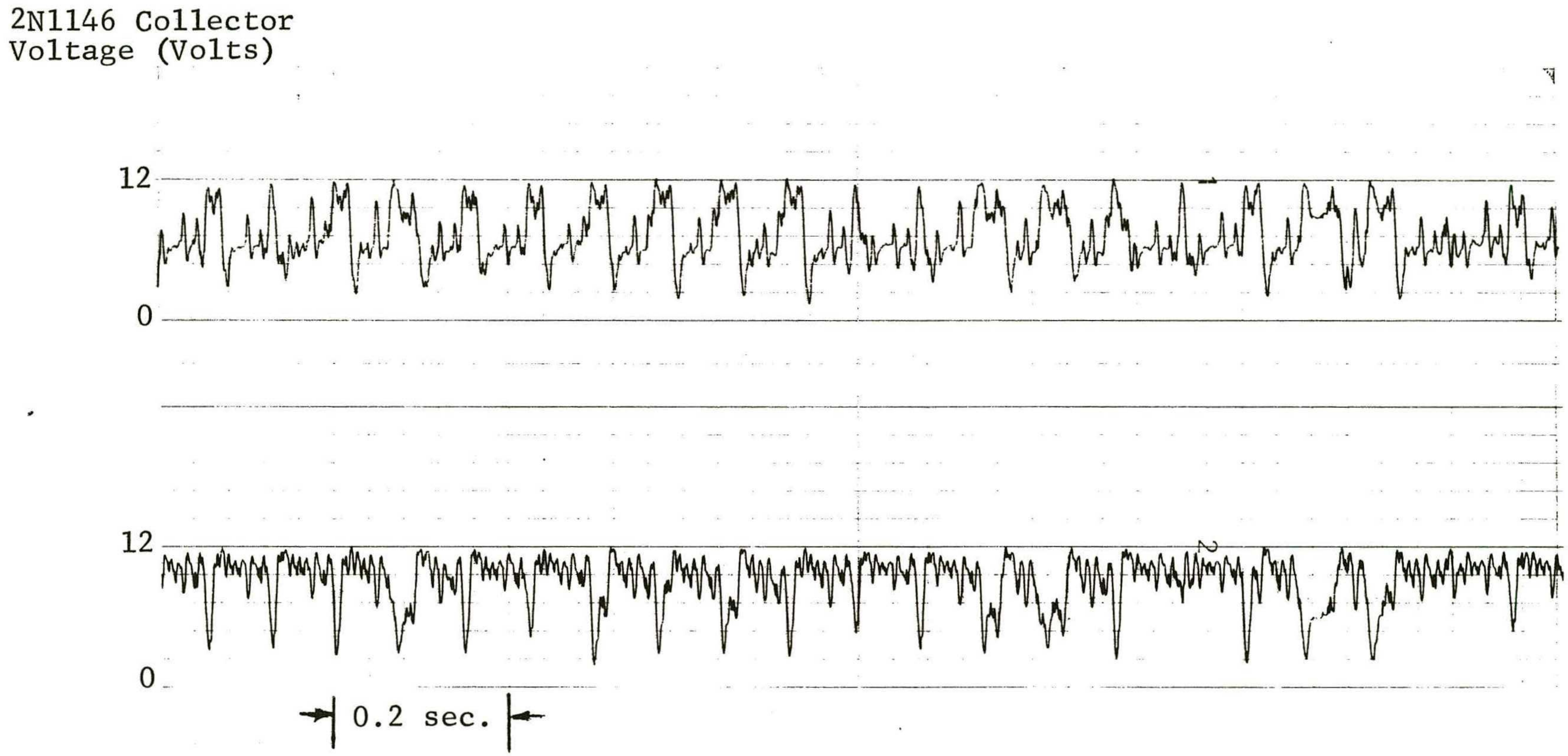

Fig. 23--Effects of noise on the output of the power transistors.

the automobile since Bender[6] showed that the magnitude of an automobile's frequency response above 0.3 Hz decreased rapidly because of the relatively long time constant associated with an automobile.

Good test results were obtained, however, in measuring the speed of the automobile while the unit was in operation. The constant speed tests were made at 45, 50, 60, and 70 miles per hour. Speeds other than these were not tested because of posted speed limits and traffic congestion. For each test involving the above listed speeds, the driver first brought the automobile up to the desired speed. The variable resistor R_2 in the control circuit was then adjusted to that desired speed setting and the circuit and magnetic clutch were engaged. Fine adjustments of R_2 usually were then made to obtain as closely as possible the desired speed.

Once the desired speed was attained, the recorder was turned on to record the speed of the automobile. Each test was conducted for about 5 minutes; portions of the recordings obtained from these tests are shown in Figs. 24 thru 27. The recording in Fig. 25 shows typical results when the automobile encountered a -5 to -10% road grade. The left portion of the figure shows that the velocity increased about 0.75 miles per hour as the automobile started down a grade. Almost 20 seconds later, the speed deviation was corrected with a slight overshoot occurring. The right portion of Fig. 24 shows the changes in the automobile's velocity as the road became level. The speed decreased only about 0.5 miles per hour and was corrected with no overshoots because of the very gradual changes in that particular road grading. Typically, deviations in speed of 0.5 to 0.75 miles per hour and overshoots of 0.25 to 0.5 miles per hour occurred when the road grading changed appreciably (See Table I).

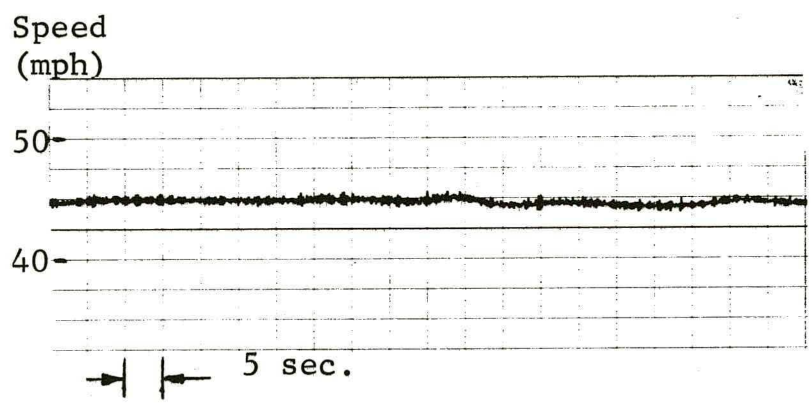

Fig. 24--Preset speed test at 45 miles per hour.

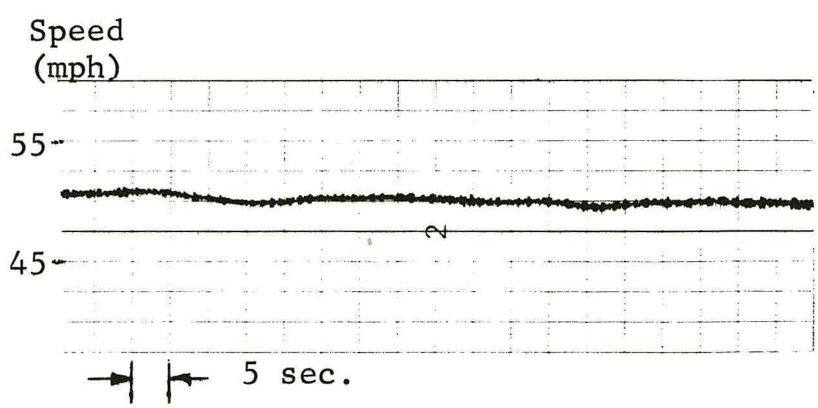

Fig. 25--Preset speed test at 50 miles per hour.

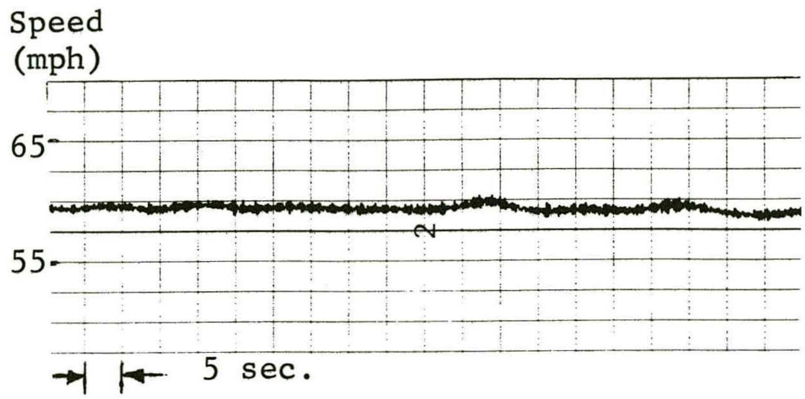

Fig. 26--Preset speed test at 60 miles per hour.

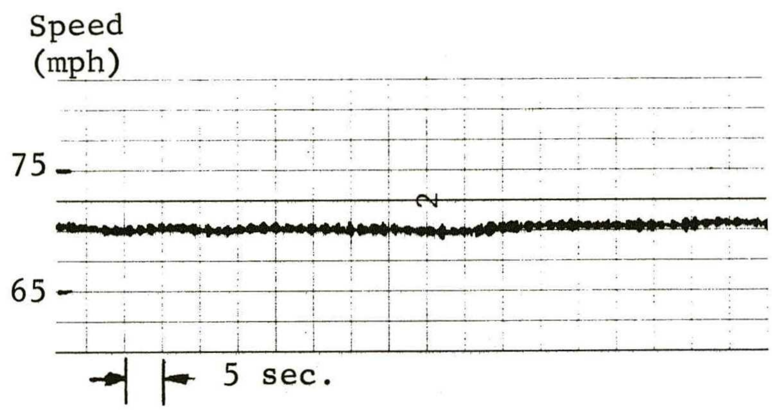

Fig. 27--Preset speed test at 70 miles per hour.

Tests were also made to determine the effect of changing the desired speed while the speed control unit was in operation. The recording equipment was the same as in the previous tests and the test procedures were very similar. The automobile was first accelerated until the desired speed was obtained. The speed control unit was then engaged and the recording equipment turned on. After several seconds at that speed, the value of the 50 kΩ variable resistor discussed in Chapter III was changed, thus causing the speed of the automobile to change. Figs. 28 and 29 show the results of two tests. In all tests the automobile made a smooth transition from one speed to another with no overshoots or oscillations. The response time seemed very adequate from the standpoint of comfort of the passengers, but was too slow for some conditions encountered on the highway.

The disengaging mechanism, consisting of an electromagnetic clutch and relay, performed satisfactorily in all situations. The driver was able to disengage the system by pressing on the brake pedal or by simply switching off the unit.

One test of the speed control circuit was made with the capacitor of the lead-compensator circuit removed, thus eliminating all lead compensation from the circuit. As expected, a limit cycle was present as shown in Fig. 30. The oscillation frequency recorded was about 0.17 Hz and the maximum deviation about ±1.5 miles per hour, very close to the predicted ±1.33 miles per hour in Chapter II.

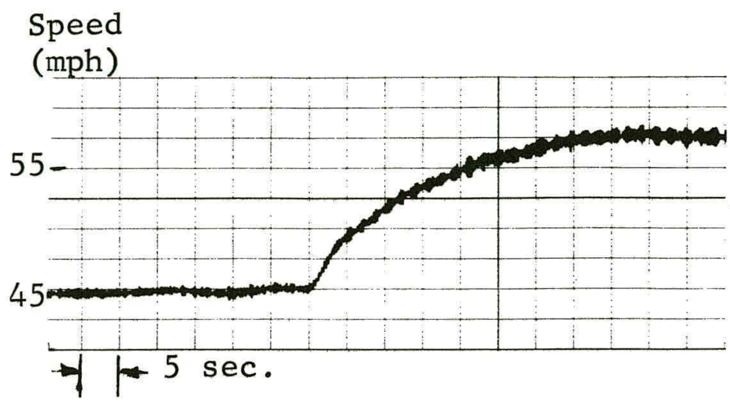

Fig. 28--Effects of changing the desired speed by a stepped change of the 50kΩ resistor.

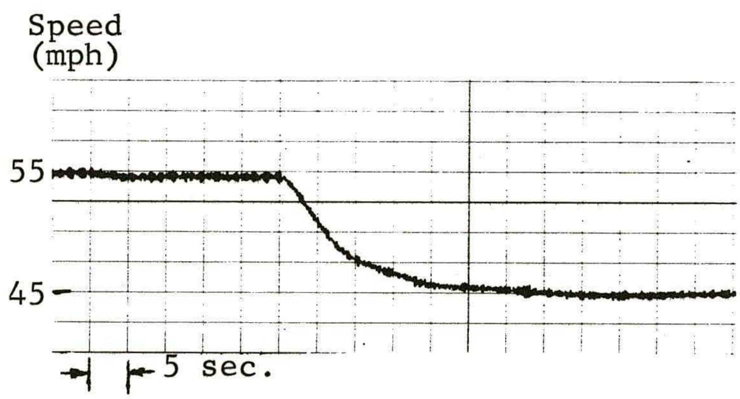

Fig. 29--Effects of changing the desired speed by a stepped change of the 50kΩ resistor.

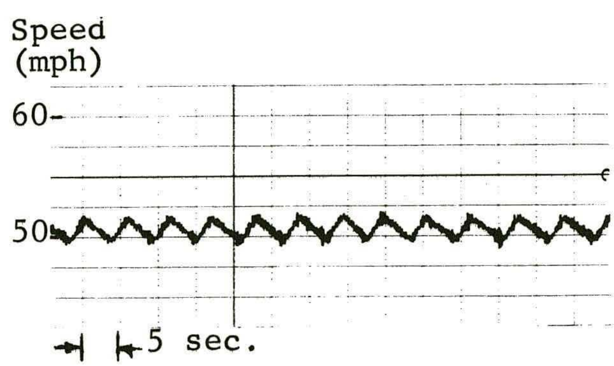

Fig. 30--Preset speed test at 55 miles per hour and no lead compensation.

CHAPTER V

SUMMARY AND CONCLUSIONS

The purpose of this study was to design, build, and test an automatic speed control system for an automobile capable of maintaining a constant, preset speed to within ±2 miles per hour under various environmental conditions.

The circuit design of the speed control unit was based on the characteristics of a relay-type servomechanism which were assumed to be somewhat analogous to a driver-vehicle, speed-control system.

The three basic components of the system were:

1. The speed selector and lead compensator circuit.
2. The switching circuit, similar in design to a relay switching circuit.
3. A motor and gear train to move the throttle linkage for controlling the speed of the automobile.

Each component was built and installed on a test vehicle.

The speeds selected for testing were 45, 50, 60, and 70 miles per hour. Results of the tests showed that the speed of the automobile was maintained to within ±0.75 miles per hour of the desired speed on variable road grades up to 10%.

One test was made with the lead-compensator circuit removed. The results of this test showed that the speed of the automobile oscillated at about 0.17 Hz and a maximum deviation of ±1.5 miles per hour.

Tests were also made to determine the effect of changing the desired speed while the system was in operation. In the several cases tested, the speed of the automobile made a smooth transition from one speed to the other with no oscillations or overshoots. The response time of approximately 25 seconds, while fine for the comfort of the passengers, was too slow for some conditions encountered while testing. Several times sudden changes in traffic ahead of the test automobile such as a vehicle suddenly changing lanes, necessitated slowing the test automobile very quickly. The response of the speed control unit was too slow so the driver had to disengage it. The long time constant of the speed selector and lead-compensator circuit was probably the major contribution to this slow response, but no testing was accomplished to determine this or a method to eliminate the problem.

Noise, presumably generated by the automobile's generator and voltage regulator, was found to be a problem in measuring the switching characteristics of the circuit. This noise blanketed the output characteristics of the power transistors used to drive the d. c. motor. Additional work on the causes and effects of the noise needs to be done.

The performance of the speed control unit compares very well to commercially available ones. The advertised capability of most commercial units is ±2 miles per hour of the preset speed, while the control unit described in this study maintained the speed to within ±0.75 miles per hour. To accurately compare them, however, tests should be run with the commercial units on the same test vehicle used in this study.

The speed control unit designed for this study represents an improvement over commercially available ones with the replacement of the complex mechanical switching circuit by a simple electronic one. The system design does have one drawback in that it requires a generated voltage proportional to the speed of the automobile. In contrast, presently available commercial units use a mechanical fly-ball governor assembly to determine this speed. The replacement of the generator by a circuit run off the ignition system would overcome this disadvantage, providing the transmission remains in the same gear. Alternate methods for determining the speed of an automobile should be investigated.

TABLE I

TEST RESULTS FOR MAINTAINING A PRESET SPEED

Speed (mph)	Approx. Test Time (min)	Desired Accuracy (mph)	Measured Accuracy (mph)
45	5	±2	±0.75
50	5	±2	±0.6
60	5	±2	±0.75
70	5	±2	±0.5

APPENDIX A

DESCRIPTION OF A COMMERCIALLY AVAILABLE SPEED CONTROL UNIT

The following is an excerpt from a 1967 brochure of the Perfect Circle Division of the Dana Corporation[9] describing their commercially available speed control unit.

> The Perfect Circle Road Speed Regulator System consists of one operating mechanism, the regulator, and an associated spring-loaded linkage system. The regulator is an electromechanical device consisting of a flyball governor assembly which is driven by a speedometer-type cable from the transmission speedometer drive connector.
>
> As terrain and winds vary, the regulator senses road speed changes and moves in a direction to allow the accelerator spring-loaded linkage to open or close the throttle for an increase or decrease in engine power, as conditions demand. This ability maintains uniform road speed within the capability of the vehicle power plant to accelerate and retard.

Since 1967, Dana Corporation has improved their speed control unit by the replacement of the motor and gear train with a vacuum-operated diaphragm. The remainder of the system is essentially the same with the flyball governor assembly used to control the system.

APPENDIX B

SENSITIVITY OF THE SWITCHING CIRCUIT

The sensitivity of the switching circuit was determined from the following requirements:

1. Operating speeds were between 40 and 70 miles per hour.
2. Maximum speed deviation was limited to ±2 miles per hour.

then

$$\frac{2}{40} > \frac{2}{70} > \text{desired sensitivity}$$

$$\approx 3\%$$

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