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SOLID STATE ELECTRONIC CONTROL SYSTEM FOR THE MACK AUTOMATIC POWER TRAIN

by

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May 3, 1974
(date)

Professor in Charge

Chairman of Department

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ABSTRACT

The author has designed a solid state electronic control system for the Mack Automatic Power Train. This system provides for control of the transmission, engine governing and road speed governing. These functions are performed digitally. A prototype was breadboarded using CMOS logic. The author considers CMOS logic to be the best choice for this system. Speed signals from the engine and transmission are provided by magnetic transducers of two different types: Hall effect and inductive.

The MAPT concept involves operating the engine at a fixed speed of 1700 rpm. Through the use of two planetary gear sets, six clutches, and two hydraulic pump/motors, an infinitely variable gear ratio is provided in the transmission. The control system provides for engaging each of the six clutches when the two halves of a clutch are exactly at synchronous speed. The driver uses a switch type selector to control the selection of the various transmission functions such as "neutral", "drive" and "reverse". The system provides for engaging each clutch at the proper instant and in the proper sequence. An interlock is provided to prevent the driver from damaging the transmission through an improper selection. The system developed consists of controlling engine

speed by loading the engine through a change in transmission ratio, and controlling road speed by varying the fuel injection pump rack position. Engine speed is controlled by varying the displacements of the two pump/motors by means of a single actuator. The actuator consists of a hydraulic cylinder controlled by a pair of solenoid valves for positioning. A floating control system with full automatic reset action operates the two valves. The engine speed input signal to the controller comes from a magnetic sensor which "counts" ring gear teeth on the engine flywheel.

The desired road speed is set by means of the accelerator pedal which transmits a command signal to the road speed governor. The actual road speed signals for this controller are obtained from a sensor located at the output shaft of the transmission. A floating control system similar to that used for engine speed control is also used for road speed governing. A rate-of-approach system has been added, however, to compensate for the response lag in the system which is represented by the necessary time required to accelerate or decelerate the complete mass of the vehicle in response to a change in the engine fuel input. Inclusion of the rate-of-approach feature permits the use of a control deadband of reduced width and results in closer control of road speed. The engine injection pump rack is positioned by an actuator consisting of a spring-return type air cylinder controlled by a pair of solenoid valves. One valve is normally-open and the other is normally-closed arranged such that when the vehicle "run" switch is turned off, air is dumped from the cylinder and the rack returns to the zero fuel position. A special feature of the control system also provides a slow speed range with full engine torque available for use when maneuvering the vehicle in loading dock areas.

INTRODUCTION

Shortly after the design concept for a new automatic power train for heavy duty trucks had been established, the author was invited by the manufacturer to propose a solid state electronic system to control clutch engagement in the transmission. The author expanded this assignment to include proposed controls for the balance of the power train. The various mechanical aspects of the transmission are still in the process of design, but a prototype will be built shortly. The electronic circuitry which comprises the complete control system was all bread-boarded and checked for proper functioning with simulated mechanical configurations.

Chapter One introduces the present practices and trends in heavy duty truck transmissions. Mechanical operation of the Mack Automatic Power Train is described in Chapter Two. Because the mechanical design is unique, the material in this chapter is necessary for a complete understanding of the control system. Chapter Three describes the operation of the clutch engagement control. Included are the various considerations involved in making accurate comparisons of shaft speeds. The material in Chapter Four comprises the bulk of the development work which resulted in the complete system. Engine speed governing and road speed governing systems are developed which provide optimum vehicle performance. The environmental conditions encountered by electronic equipment installed on vehicles are covered in Chapter Five. This chapter is important if the design considerations for the system are to be appreciated. The speed sensors selected for the system, together with their characteristics, are covered in Chapter Six. Chapter Seven discusses available logic types and the considerations which led to the selection of CMOS logic for the system. Detailed descriptions and schematic diagrams of all circuitry involved in the system are contained in Chapter Eight. Chapter Nine relates the electronic control system to the final mechanical design of the transmission.

CHAPTER 1 - THE TRUCK TRANSMISSION

For many years a standard feature of heavy duty trucks has been a manually shifted transmission which permits the driver to operate the engine under conditions of maximum power for a given road speed. This transmission frequently assumes the form of a five speed main gear box driving into a two or a three speed auxiliary gear box so as to provide either ten or fifteen forward speeds. Each of the two gear boxes has its own shift stick. By proper manipulation of the two shift sticks the driver is able to select the proper over all gear ratio to permit the engine to operate at optimum conditions for a given road speed. Considerable skill and diligence on the part of the driver are required, if the maximum efficiency is to be obtained, particularly when the vehicle is operating in mountainous terrain.

Following the trend in passenger car practice certain automatic transmissions designed for use in heavy duty trucks have appeared. These transmissions effectively remove the human element and assure optimum operating conditions at all times. These automatic transmissions also reduce driver fatigue and therefore contribute to safety in operation of the vehicle. Unfortunately the efficiency of most automatic transmissions is lower than that of a conventional manually shifted gear box. This reduced efficiency of the automatic transmission results from the use of a hydraulic fluid coupling or a torque converter.

In order to overcome the poor efficiency of the conventional automatic transmission several new semi-automatic transmissions have been developed. These are in effect conventional manually shifted gear boxes which have been converted to automatic shift by a series of external actuators directed by an electronic controller. Instead of a conventional shift stick, the driver moves a switch-type selector lever. The Dana SST-10 transmission is an example of this type of unit. Semi-automatic operation is achieved with an electric clutch and brake. Air controls and a solid state electronic package are designed into the unit to control synchronizing and shifting functions. The control provides for continuous electronic monitoring so as to properly sequence the mechanical events that must take place (clutch engagement and disengagement, shifting and synchronization). If an imbalance occurs in the system because the driver selected a new gear ratio, the logic system activates a predetermined sequence to re-establish the balance between the selector switch and the various transmission ratios. The control system also compensates for driver error, thus protecting the transmission from damage.

Meanwhile manufacturers of the conventional type of automatic transmission, such as Allison, have been making changes in their units to improve efficiency and obtain better control over the performance. For use in conjunction with their largest transmissions, Allison has announced the new automatic electric shift control which is a miniature electronic computer known as a shift pattern generator. Electric signals flow continuously from the vehicle operators station, as well as from the engine and the output point of the transmission itself, into the transistorized device. By constantly evaluating each of these signals, the shift pattern generator selects the best gear range for the work the engine-transmission package is doing at any given moment. If gear up-shifts or down-shifts are needed they are ordered by the automatic shift control.

A further development in the automatic transmission field is a new transmission being marketed by the Cummins-Sundstrand Corporation which combines the best features of hydrostatic and mechanical transmissions. This transmission employs two power paths, one mechanical and the other hydraulic. Under normal conditions the amount of power transmitted by the hydraulic train varies from zero to 35 percent of engine power. The distribution of power between the two trains is adjusted automatically as dictated by the requirements of the operating conditions. The effect of this division of power between the two trains is to produce an infinitely variable ratio characteristic which optimizes the engine-transmission overall efficiency.

When the Mack Automatic Power Train (MAPT) was being designed it was decided to use the hydro-mechanical approach. It was further decided that the engine would be operated at a constant speed. This concept permits designing for optimum conditions at a single engine speed and assists in the problem of minimizing engine pollutants.

CHAPTER 2 - THE MACK AUTOMATIC POWER TRAIN

A schematic diagram of the transmission is shown in Figure 1. Power is transmitted from the input shaft to the output shaft through an infinitely variable ratio system consisting of four separate ranges. As shown in the diagram, there are two planetary gear sets, two hydraulic variable displacement pump/motors and six clutches. The planetary and hydraulic units are organized into two component groups interconnected by the six clutches. The first component group is made up of the first planetary and the two hydraulic units and produces two outputs whose speed changes with the relative displacements of the hydraulic units. The second component group consists of the second planetary gear set whose function is to split the outputs of the first component group to give a total of four ranges.

In detail, the first planetary is shown in Figure 2. The purpose of this planetary is to provide two outputs, ① and ③, both turning in the same direction and whose speeds are determined by the relative displacements of the hydraulic units. When the speed of one of these shafts increases the speed of the other decreases. One of the hydraulic units is connected to gear ㉝ and the other is connected to gear ③. It can be seen that when the displacements of the two

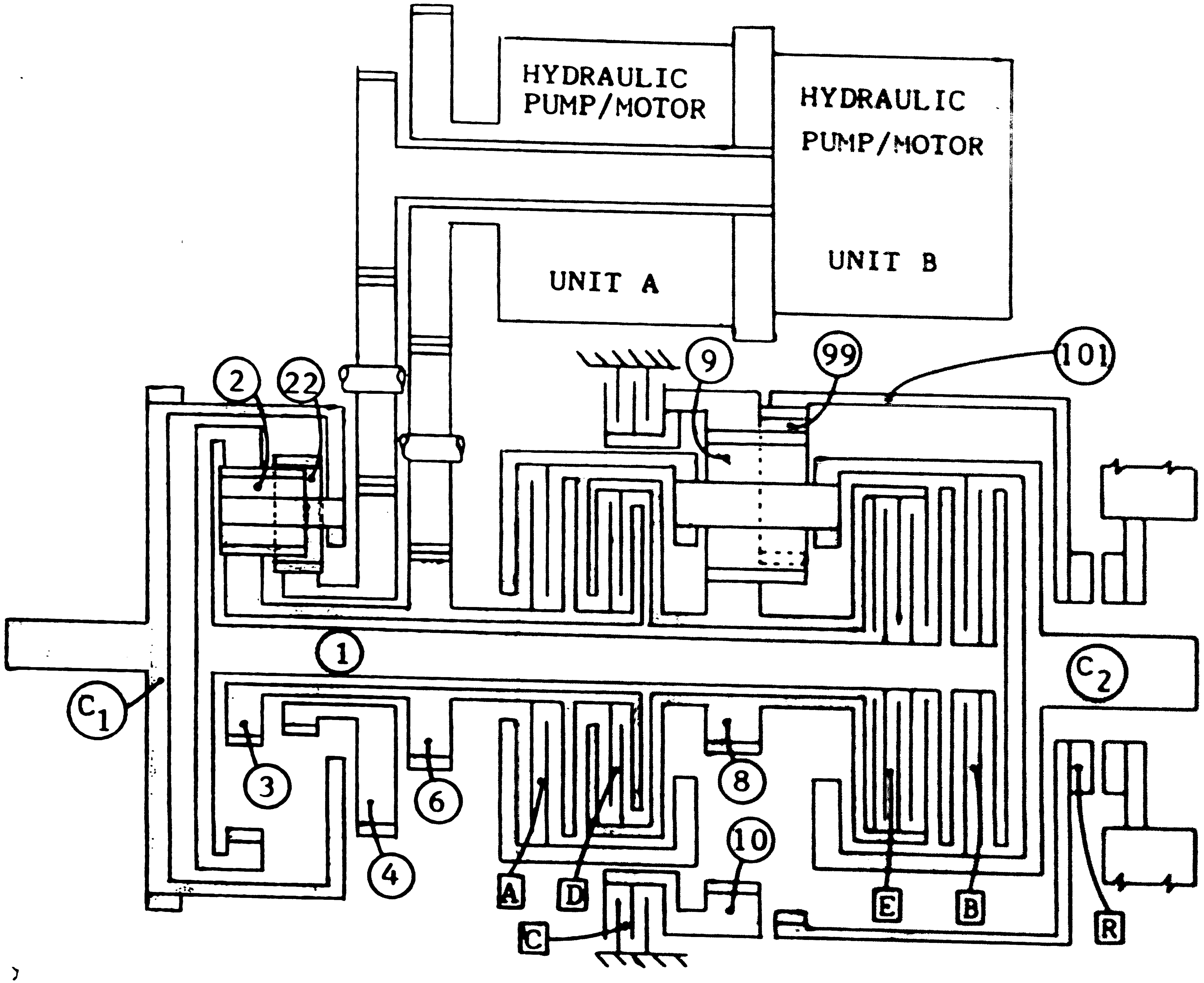

FIGURE 1 FOUR RANGE HYDROMECHANICAL TRANSMISSION

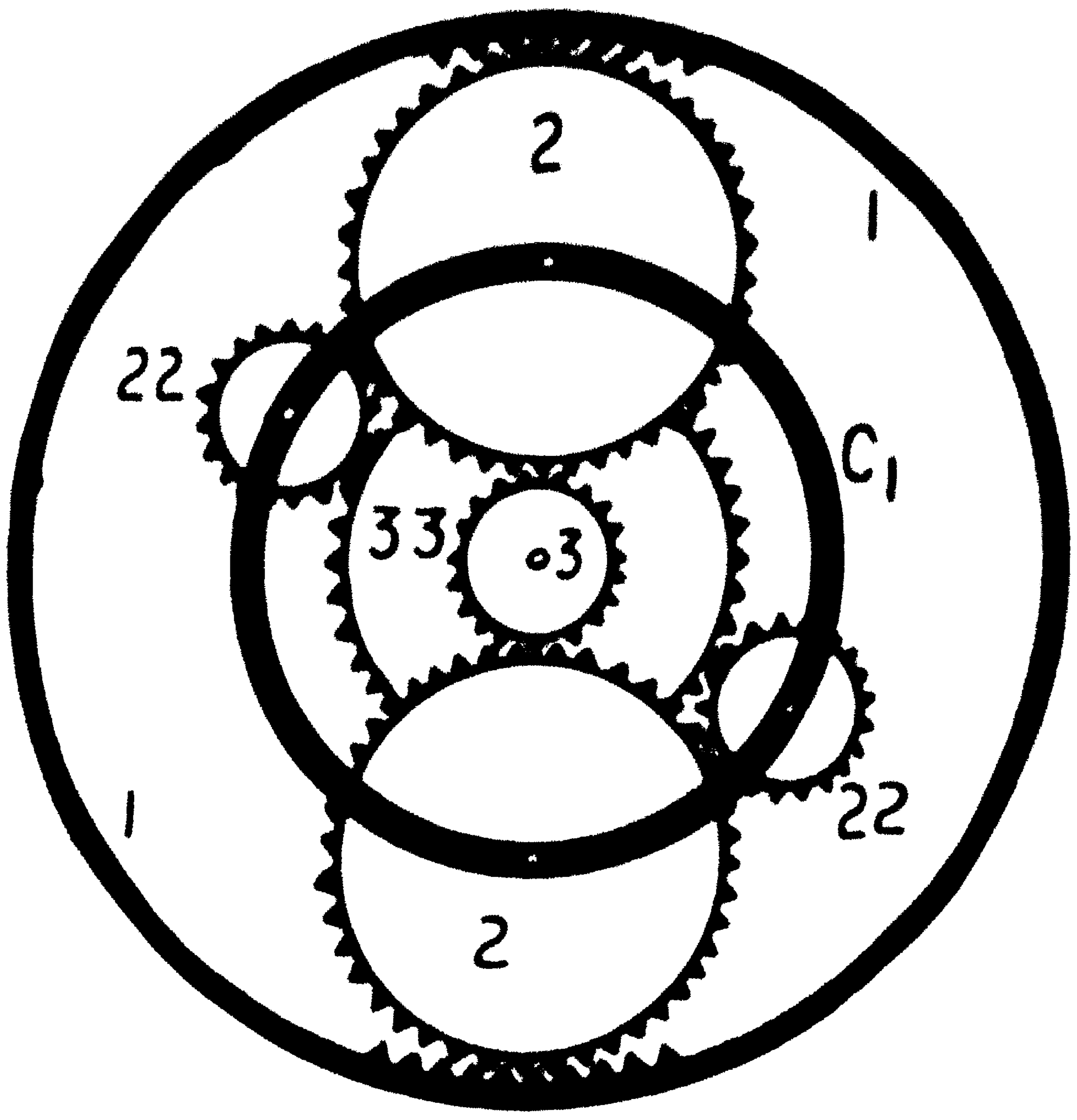

FIGURE 2 FIRST PLANETARY

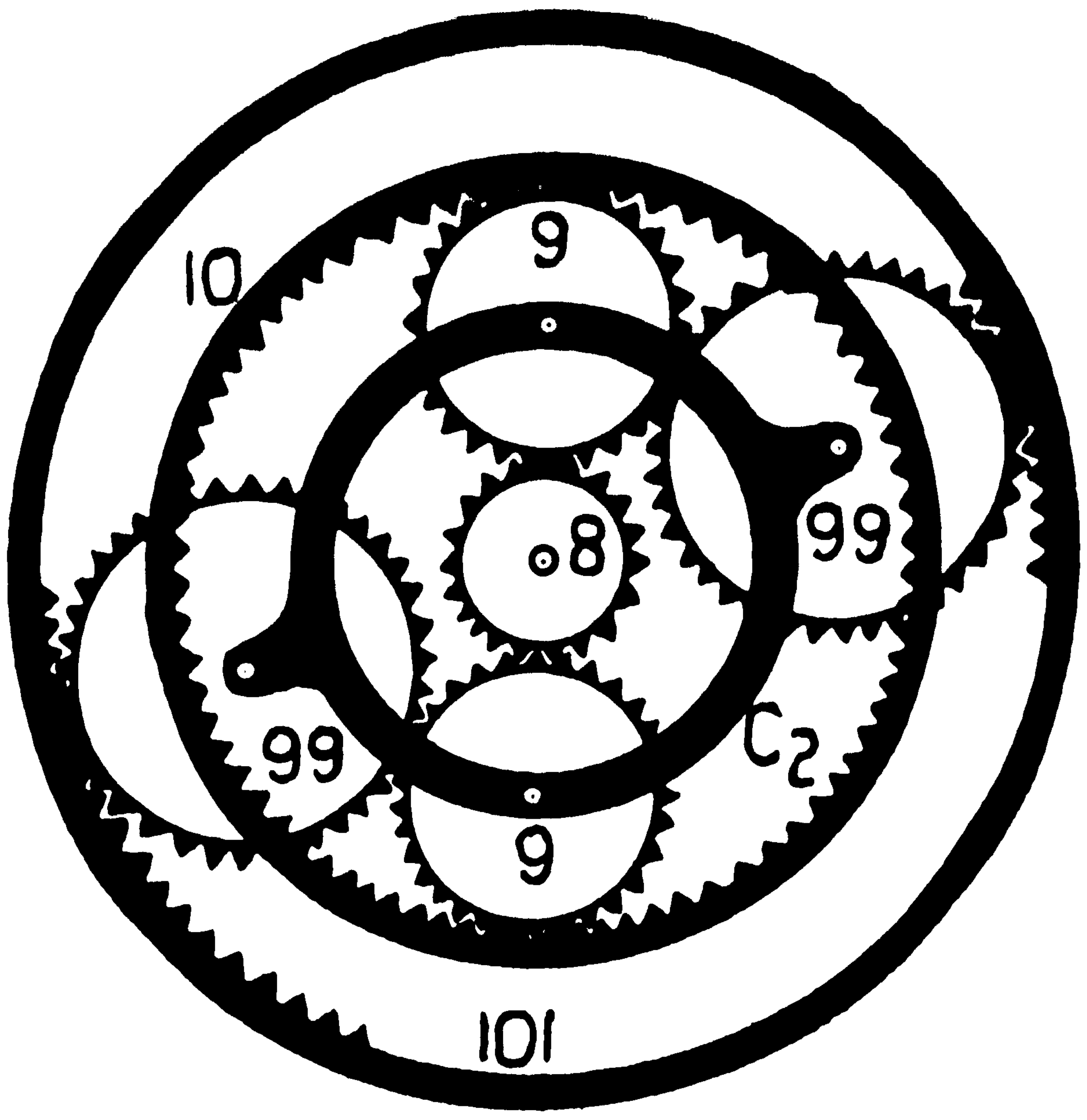

FIGURE 3 SECOND PLANETARY

hydraulic units are the same, gears ③ and ㉝ would be turning at the same speed and therefore gears ③ and ① would turn at the same speed. Furthermore, if the displacement of the hydraulic unit connected to gear ㉝ is decreased such that this hydraulic unit turned faster than the one connected to gear ③ , it would appear as though gear ① should turn faster than gear ③. However, from the plot of planetary member speed in Figure 4 we see that gear ① never turns faster than gear ③ . The explanation is that the hydraulic unit connected to gear ㉝ turns 1.9 times as fast as gear ③ while the hydraulic unit connected to gear ③ turns only 0.76 times as fast as gear ③ .

A diagram of the second planetary is shown in Figure 3. The purpose of this planetary is to step down the speeds of shafts ① and ③ . Thus two outputs are available from this stage, direct and times 0.213. Since two input speeds are provided we therefore have four output speeds available.

This transmission provides an infinitely variable ratio obtained through four ranges. In range I shaft ① is connected to the output shaft (C2) through clutches 🄲 and 🄴 and the reduction of the second planetary. In range II shaft ③ is connected to the output shaft through clutches 🄲 and 🄳 and the reduction of the second planetary. In range III shaft ① is coupled directly to the output shaft through clutch $\boxed{B}$. In range IV shaft ③ is coupled directly to the output shaft through clutch $\boxed{A}$.

To obtain a clearer picture of the manner in which operation of the various ranges supply power to the output shaft refer to Figure 4. In range I the speed of shaft ① increases and produces a corresponding change in the speed of the output shaft, the difference in rate being due to the reduction of the second planetary. In range II, shaft ③ increases with a corresponding increase in the output shaft, and again the difference in rate is due to the reduction of the second planetary. In range III, since shaft ① is directly coupled to the output shaft, the speeds of the two shafts are the same. In range IV, shaft ③ is directly coupled to the output shaft and again the speeds of the two shafts are the same. It will be noticed from Figure 4 that the engine speed (member (C1)) is constant at 1700 rpm except for the first half of range I. The decrease in speed at this point is necessary to prevent overspeeding gear ③ .

Provision for operating the vehicle in reverse is obtained by engaging clutch $\boxed{R}$ in place of clutch $\boxed{C}$.

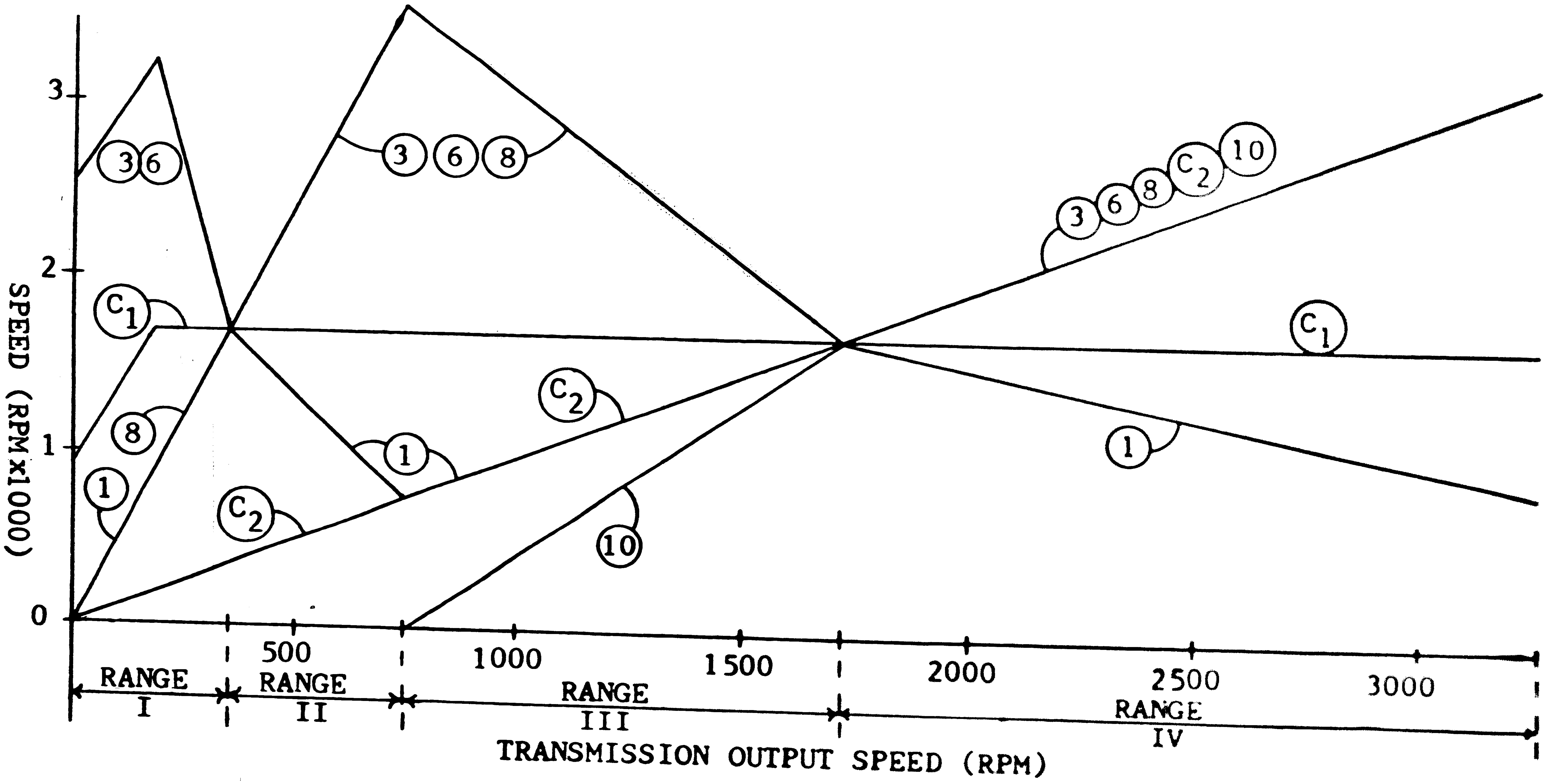

FIGURE 4 PLANETARY MEMBER SPEED

This locks up member (101) rather than member ⑩ and causes (C2) to rotate in the opposite direction, as seen in Figure 3.

CHAPTER 3 - THE CLUTCH ENGAGEMENT CONTROL

The transmission control can be broken down into two parts: a clutch engagement control and an engine speed control. The clutch control is designed to engage the clutches in the proper order when the two members of the clutch are at synchronous speed. The obvious method for measuring the speeds of the two members is to count gear teeth over a period of time. Two magnetic sensors would be used for this purpose. This method, however, is satisfactory only when the speeds of the two members are relatively constant or changing slowly.

In this application the speed of one member is increasing while the speed of the other member is decreasing, and it is necessary to determine the exact instant when the speeds of the two members of the clutch are equal. It was decided therefore to measure <u>period</u> instead of frequency. This reduces the measurement interval. The limitation of this method is only the accuracy of gear tooth spacing. The sine wave output signal from each magnetic sensor is fed into a Schmitt trigger which produces a square wave. In order to compensate for a possible lack of symmetry of the square wave, resulting from non-linearity of the sine wave from the pickup and/or the Schmitt trigger, the frequency of the square wave is divided by two. It can be demonstrated that this technique effectively eliminates differences in the on-times of the two square waves. These on-time differences might result from differences in the signals from the two sensors because of different gear tooth widths on the two rotating members. As designed, the period comparison circuit requires a maximum of three input pulses for accurate determination of identical period. The finite detection time can be calculated as follows:

In a shift between ranges I and II, clutches $\boxed{C}$ and $\boxed{D}$ are engaged and therefore members ① and ⑥ must be compared for synchronous speed. In a shift from range II to range III or in a shift from range IV to range III, clutch $\boxed{B}$ is engaged and therefore members ① and $\textcircled{C_2}$ must be compared. In a shift from range III to range IV, clutch $\boxed{A}$ is engaged and members ⑥ and $\textcircled{C_2}$ must be compared. In a shift from range III to range II, clutch $\boxed{C}$ is engaged. However, since one-half of clutch $\boxed{C}$ is connected to the transmission case, the two halves of clutch $\boxed{C}$ are not compared. Instead, we can take advantage of the fact that when the speed of member ⑩ is zero, the following relationship holds between members ⑧ and $\textcircled{C_2}$; $(b+a)/a$ revolutions of ⑧ = 1 revolution of $\textcircled{C_2}$, where a = the number of gear teeth on ⑧ = 23 teeth and b =

the number of gear teeth on ⑩ = 85 teeth. Thus, 108 revolutions of ⑧ must provide the same number of sensor pulses as 23 revolutions of (C_2). Therefore, since ①, ⑥, ⑧ and (C_2) are compared for synchronous speeds, let ①, ⑥, ⑧ and (C_2) all have the same number of teeth read by the sensor and let this be 46 teeth. For the range III to range II shift, we need a second output from (C_2) with 108 pulses per revolution. Call this output (nC_2). Then for the range III to II shift, compare the period of the pulses from (nC_2) to twice the period of the pulses from ⑥ (divide the frequency of the pulses from ⑥ by two).

The equation for the sense time for a shift between two ranges is:

$$\frac{\text{60 sec/min X 3 pulses}}{\text{speed of the two members X number of pulses per revolution of the members}}$$

The 60 sec/min is used to convert the speed of the members being compared from rev/min to rev/sec. The 3 pulses come about due to the fact that 3 input pulses are necessary for the comparison circuit to compare period. Thus, the sense time for a shift between ranges I and II or between ranges III and IV, where we are comparing members ① , ⑥, and (C_2) at a speed of 1700 RPM, is 2.3 milliseconds. The sense time for a shift from range II to range III, where members ① and $\textcircled{C_2}$ are compared at a speed of 745 rev/min, is 5.25 milliseconds. The sense time for a shift from range III to range II, where 1/2 the speed of ⑥ (23 pulses/rev @ 3500 RPM) is compared to $\textcircled{nC_2}$ (108 pulses/rev @ 745 RPM), is 2.24 milliseconds. Thus the maximum sense time anywhere in the clutch control circuit is only 5.25 milliseconds.

Hydraulic actuation of the clutches is provided with solenoid valves controlling the hydraulic cylinders. A typical solenoid valve has an operating time of ten milliseconds. Operating time for the hydraulic cylinders is something in excess of one hundred milliseconds, so it is clear that the electronic and electro-mechanical portions of the system are faster than the hydraulic actuating means. Control of the transmission is by a selector lever or push-button assembly available to the driver with the following positions: Start, Neutral, Reverse, Drive Low and Drive High. It will be noted that a Park position has been omitted. This would be superfluous in view of the fact that spring brakes for parking are standard on all heavy duty trucks.

<u>Start</u> - In this position it is possible to start the truck by pushing or towing in the event that the truck has weak batteries. Clutch $\boxed{B}$ is deliberately engaged

which effectively puts the transmission in range III. As soon as the engine starts the selector lever can be moved to neutral to allow the engine to continue running while the vehicle is parked.

Neutral - With the selector lever in neutral, all six clutches are disengaged which eliminates any transmission of power from the input shaft to the output shaft of the transmission.

Reverse - With the selector lever in this position, the transmission is in "drive low", with Clutch $\boxed{R}$ engaged in place of Clutch $\boxed{C}$.

Drive Low - The purpose of this position, is to allow for low speed operation of the vehicle as when maneuvering around loading docks. Vehicle speed is limited to ten percent of normal, but full engine power is still available. Clutches $\boxed{C}$ and $\boxed{E}$ are engaged as when operating in range I.

Drive High - This is the position of the selector lever in which the truck normally would be driven. At minimum throttle, Clutches $\boxed{C}$ and $\boxed{E}$ are engaged, the engine is at idle and the displacements of the hydraulic units are controlled such that the output shaft speed is zero. At this time the transmission is in range I. As the driver increases the throttle, the engine speed increases as shown in Figure 4 and the displacement of hydraulic unit A increases while the displacement of hydraulic unit B decreases as shown in Figure 5. As truck speed increases such that the two halves of Clutch $\boxed{D}$ are at the same speed, Clutch $\boxed{D}$ is engaged. After Clutch $\boxed{D}$ is engaged, Clutch $\boxed{E}$ is disengaged and the transmission goes from Range I to Range II. To increase the speed of the truck in Range II, the displacement of hydraulic unit A is decreased while the displacement of hydraulic unit B is increased. As truck speed further increases to the point where the two halves of Clutch $\boxed{B}$ are at the same speed, Clutch $\boxed{B}$ is engaged after which Clutch $\boxed{C}$ is disengaged and the transmission goes from Range II to Range III. To increase the speed of the truck in Range III, the displacement of hydraulic unit A is increased while the displacement of hydraulit unit B is decreased, as in Range I. After a further increase in truck speed, the two halves of Clutch $\boxed{A}$ will be at the same speed. At this time Clutch $\boxed{A}$ is engaged, Clutch $\boxed{B}$ is disengaged and the transmission goes from Range III to Range IV. To increase the speed of the truck in Range IV, the hydraulic units are varied the same as in Range II; the displacement of hydraulic unit A decreases while that of B increases. A decrease in throttle indicating desire for lower speed causes the displace-

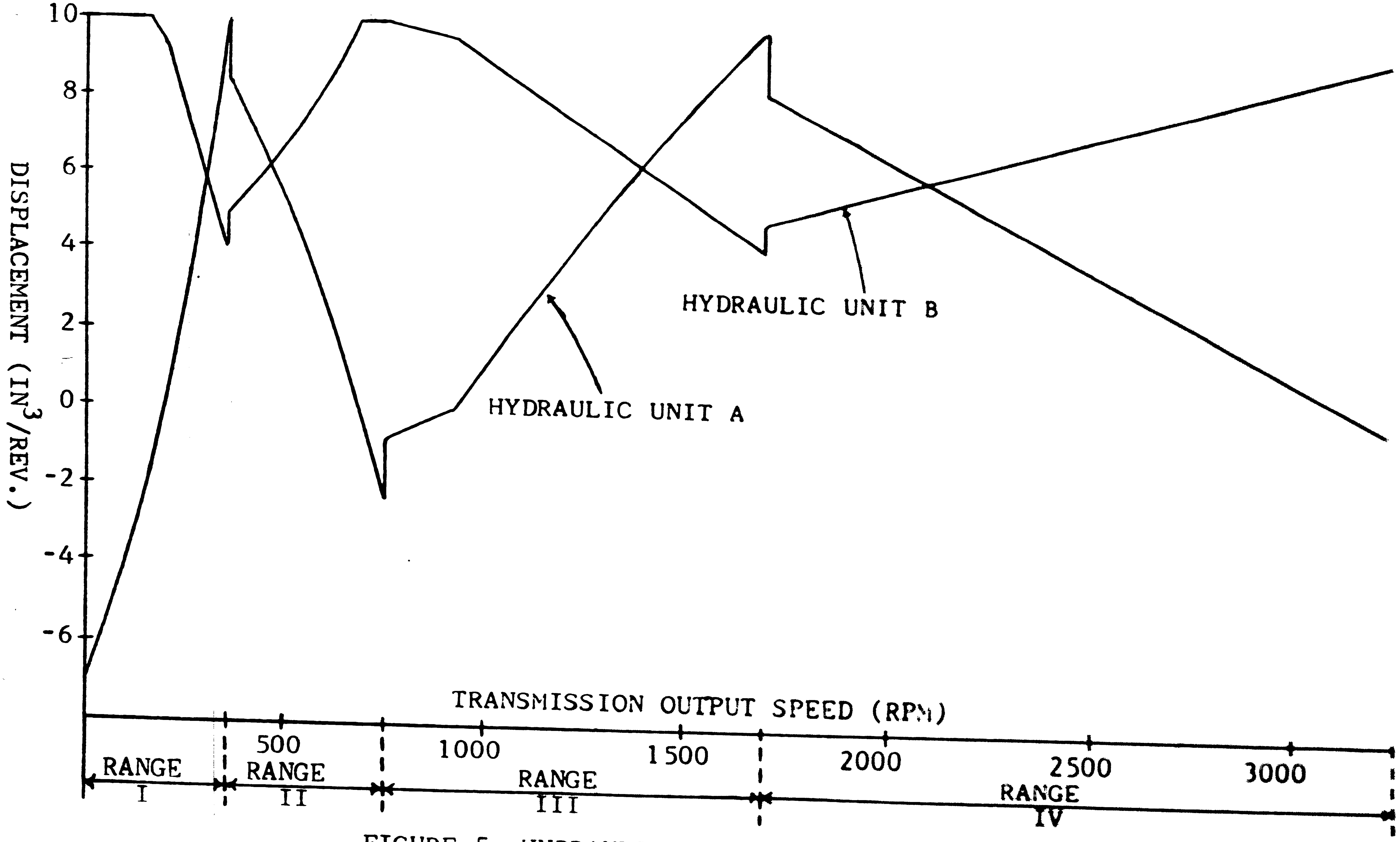

FIGURE 5 HYDRAULIC UNIT DISPLACEMENT

ment of hydraulic unit A to increase and the displacement of unit B to decrease and the transmission goes back down through the ranges, from IV, to III to II to I, until the proper speed is obtained.

To prevent the driver from damaging the transmission through an incorrect selection of operating mode, an electrical interlock is provided which ignores the improper selection and sounds an alarm. The permissible selector lever sequences are as follows: from "start" to "neutral" any time; from "neutral" to "start" only when the engine is not running; between "neutral", "reverse", "drive low" and "drive high" only when the engine is at idle and the truck is not moving. An interlock is also provided to prevent cranking the engine unless the transmission is in neutral.

CHAPTER 4 - ROAD SPEED AND ENGINE SPEED GOVERNING

Controlling the Vehicle by Means of the Transmission

As stated previously, one of the concepts of the MAPT is to operate the engine at a constant speed of 1700 RPM. Logically this 1700 RPM must be maintained by a mechanical or an electrical governor. Vehicle road speed could be controlled by varying the transmission ratio. As shown in Figure 6, input commands to the transmission control are supplied from a roadspeed governor whose set point input is provided by the accelerator pedal of the vehicle. For example, to maintain a constant roadspeed of 35 miles per hour, the transmission controller will vary the ratio of the transmission as required to maintain this speed as the truck goes up and down hill. As more or less engine power is required the engine governor will vary the fuel control rack of the injection pump accordingly.

Unfortunately, this simple control system has several inherent problems. First of all, there is no provision to accommodate loads on the vehicle at a given road speed which are greater than the horsepower capabilities of the engine. For example, with a given vehicle weight and road grade it may not be possible to maintain 55 miles per hour with the size of the engine installed in the vehicle. As the vehicle moves up a

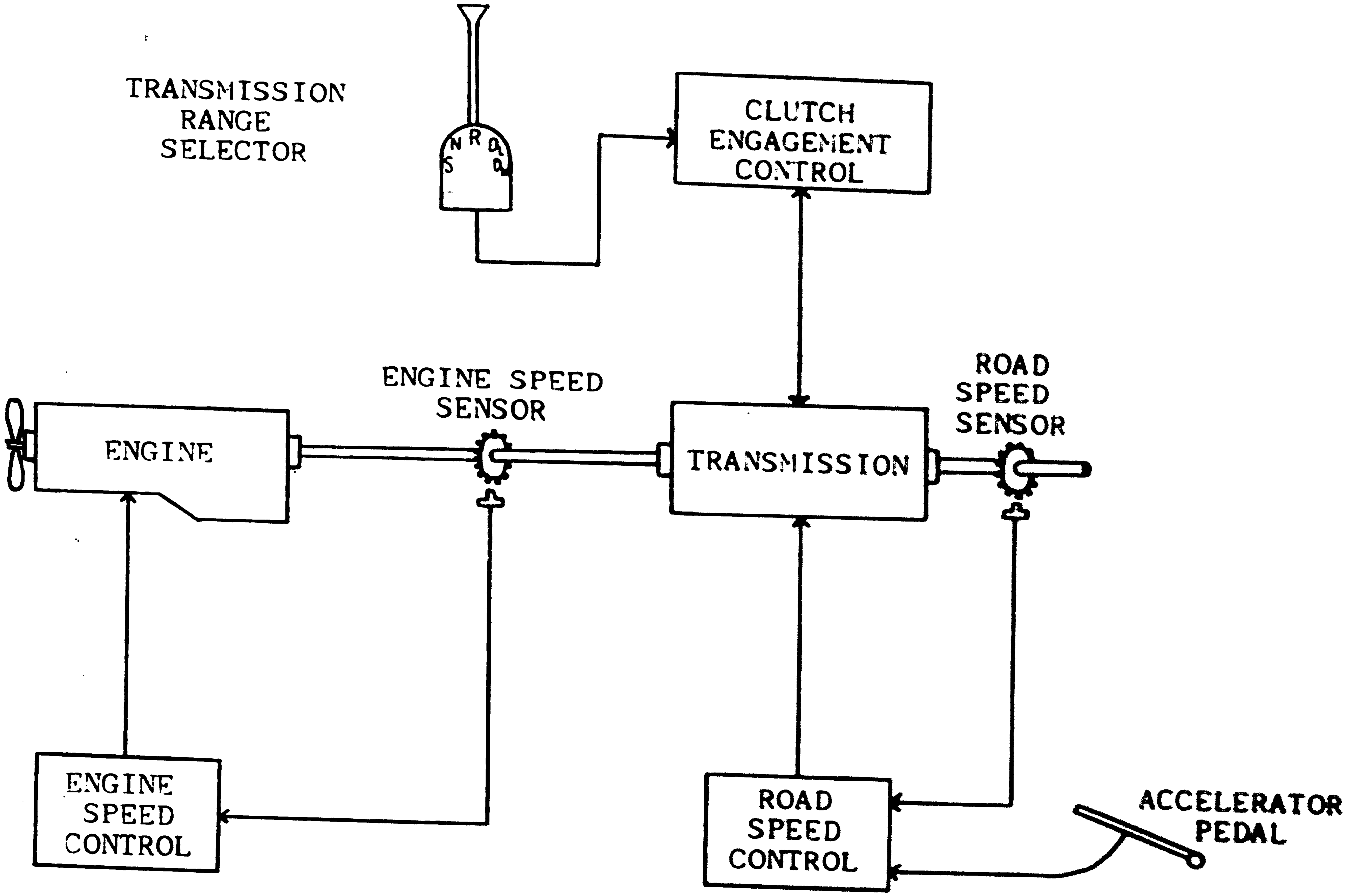

FIGURE 6 CONTROL SYSTEM FOR ENGINE AND TRANSMISSION

hill we reach a point where the engine is supplying maximum horse power with the injection pump rack in the full fuel position. If the road speed decreases below the set point, the transmission controller will change the transmission ratio in an attempt to maintain road speed by decreasing the overall gear ratio. A decrease in gear ratio, however, increases the load on the engine. When we have reached the operating condition where the engine governor has produced a full throttle condition, any further attempt by the transmission control to maintain road speed can result only in a decrease in engine speed. This could result in eventual stalling of the engine. The driver can avert this catastrophe, however, by backing off the setting on his accelerator pedal and allowing road speed to drop sufficiently to maintain 1700 RPM engine speed. Automatic means can be provided, however, to avoid relying on the driver to back off on his accelerator setting. This means would sense any decrease in engine speed below 1700 RPM with the rack in the full fuel position. The resulting signal would be used to reset the roadspeed governor to a lower value to maintain engine speed at 1700 RPM.

The second problem with this control system, however, results from the fact that there is no tendency towards self-regulation. Let us consider the case where engine speed may increase slightly. This increase in engine speed will cause a corresponding increase in road speed. If this increase in road speed is within the deadband of the road speed controller, nothing happens. If the road speed controller deadband is exceeded, however, the transmission ratio will be decreased so as to unload the engine and further increase engine speed. This could be an inherently unstable condition inasmuch as the additional increase in engine speed caused by the transmission controller will require the engine governor to operate to bring the speed back down. This change in engine speed, however, will in turn actuate the road speed controller and continual interaction between the two control systems will result.

The foregoing problems can be further aggravated due to the small changes in transmission efficiency which occur throughout the operating range. See Figure 7. If you consider operation at point A on the efficiency curve, it will be noted that efficiency increases quite steeply for a small decrease in road speed and/or a small decrease in overall transmission ratio. This increase in efficiency serves further to decrease the load on the engine. This results in a momentary increase in engine speed similar to, but of an even

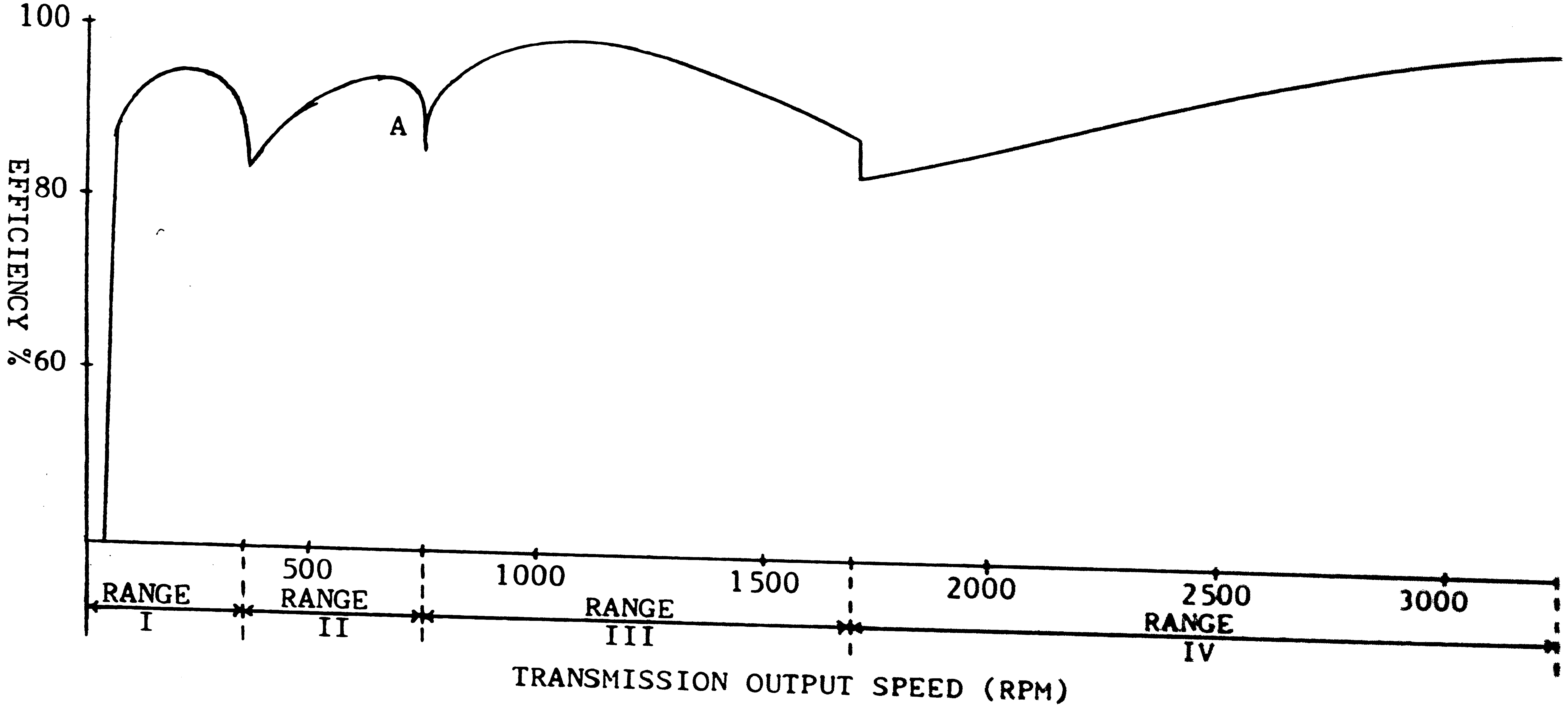

FIGURE 7 TRANSMISSION EFFICIENCY

greater magnitude than, the phenomenon previously described. It also becomes obvious at this point that the speed versus load characteristic of the engine is important if a smoothly operating power train is to be obtained. Engine characteristics should be tailored at the operating point, such that a decrease in horsepower occurs with an increase in engine speed, as shown in Figure 8. This drop-off of engine power as engine speed increases will compensate for the increase in efficiency of the transmission, and thus contribute to the inherent damping of the control system.

Improved Control System

Most of the problems noted with the foregoing control system can be eliminated by controlling road speed by varying engine fuel injection pump rack position, and by controlling engine speed by varying transmission ratio. This system is shown diagramatically in Figure 9. The action of the transmission control in this system is to vary the transmission ratio so as to unload the engine as the engine speed decreases and load the engine as the engine speed increases. This eliminates the problem previously mentioned where the engine could be stalled by an attempt of the controller to maintain road speed under conditions of heavy load. Now as the vehicle climbs a hill engine speed and road speed begin to drop

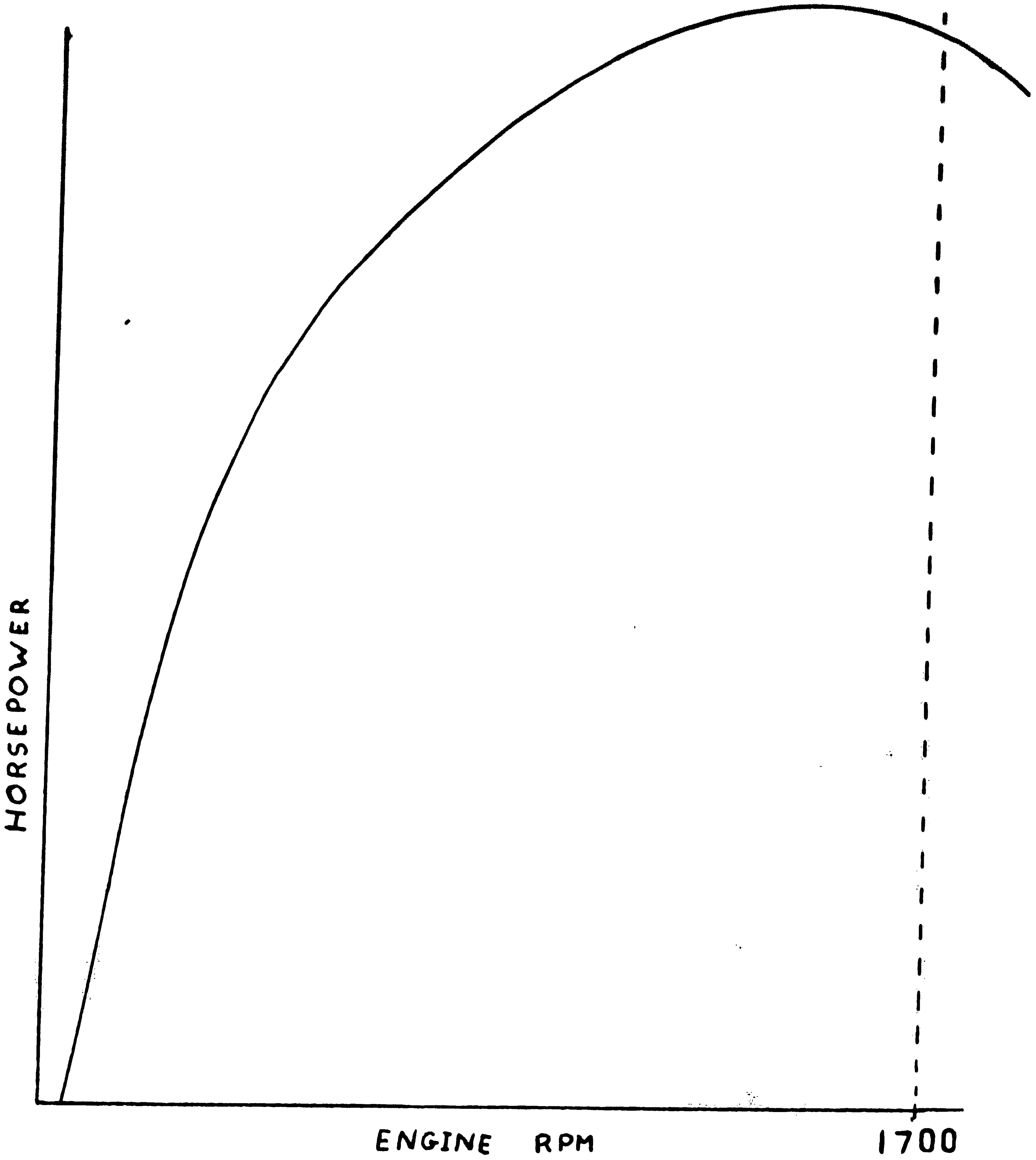

FIGURE 8 ENGINE HORSEPOWER CURVE

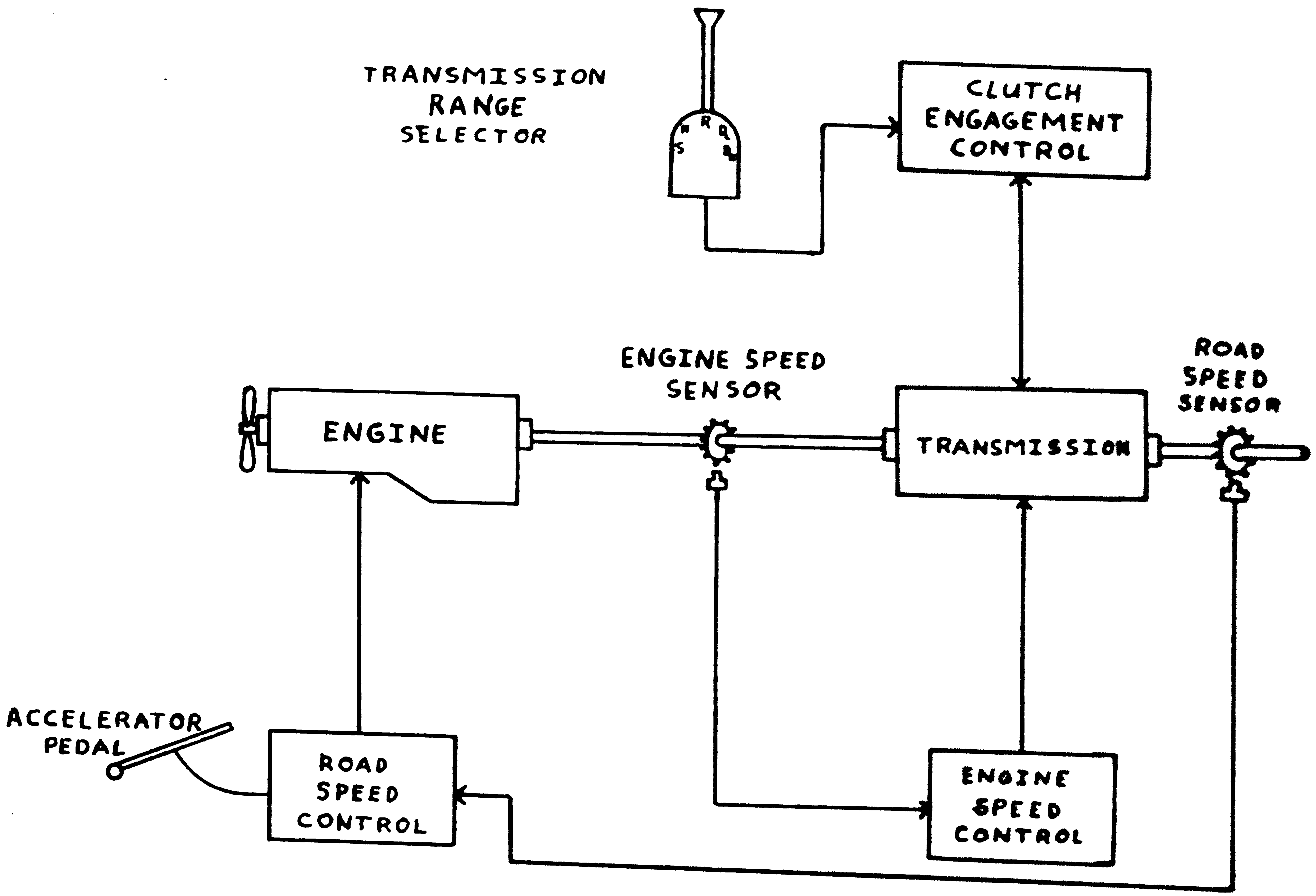

FIGURE 9 IMPROVED CONTROL SYSTEM FOR ENGINE AND TRANSMISSION

off. The two controllers operate almost simultaneously, with the road speed controller producing a further advancement of the rack and the engine speed controller changing the transmission ratio so as to unload the engine to maintain 1700 RPM. It should be noted that both the engine speed and road speed controllers operate to maintain the engine speed at 1700 RPM. Since both of these controllers operate in the same direction there is no interaction which would produce an unstable control system. It should be understood that small changes in road speed conceivably could produce a change in injection pump rack setting which would be sufficient to return road speed to the set point, without actuation of the engine speed controller, and without a change in transmission ratio. As the vehicle begins to descend a grade, engine and road speeds are maintained at the set point by readjustment of the two controllers in a manner exactly opposite to that when the vehicle was going up the hill.

A problem not previously considered is that of permitting the truck to come to a complete stop without stalling the engine. When the driver removes his foot from the accelerator pedal and steps on the brake, the road speed governor calls for zero road speed which returns the injection pump rack to the minimum fuel position. The engine speed controller down-shifts the transmission in an attempt to maintain engine speed at 1700 RPM. As the vehicle slows down, the reader might expect that engine speed will continue to decrease until the idle value is reached with the vehicle stopped, except that with this transmission there is a special problem. Referring to Figure 5 it can be seen that, at zero road speed, hydraulic unit B has a displacement of 10 cubic inches per revolution and hydraulic unit A has a displacement of minus 7 cubic inches per revolution. The problem is to position the actuator at the proper point to maintain the displacement of hydraulic unit A exactly at the point which corresponds to zero miles per hour. It can be seen that if the displacement of unit A is too large in the negative direction, the output shaft will tend to turn in the reverse direction which will cause the vehicle to move backwards. It is obvious from the mechanical design, that this positioning requirement can be met by proper design of the road speed governor, so that when zero miles per hour is sensed, the transmission is shifted into neutral and the engine speed is maintained at idle by controlling the rack position.

An optional simplification of this system would consist of eliminating the road speed governor and controlling the injection pump rack directly from the accelerator pedal. The election of this option sacrifices the possibility of including a cruise control for the vehicle. This feature is considered to be a definite convenience when operating vehicles on interstate highways. The problem of bringing the vehicle to a stop without stalling the engine also must be resolved by some other means if the road speed controller is to be eliminated.

Engine Speed Controller

Engine speed is controlled by varying engine load through a change in transmission ratio. Rotational speed of the engine flywheel is sensed by counting ring gear teeth. The controller produces an output signal which is used to position a pneumatic or hydraulic actuator connected to the control lever of the hydraulic pump/motor units in the transmission. The actuator is positioned by means of a single speed floating control system which supplies air or hydraulic fluid to the actuator to produce movement through its entire range. A pair of solenoid valves is used to control the fluid pressure applied to the actuator. One valve connects to a source of high pressure and moves the actuator in the increase direction. The second solenoid valve is a bleed or dump valve and causes the actuator to move in the decrease direction.

The solenoid valves in turn are controlled by increase and decrease signals from the controller, but a deadband is provided between these two signals. This is done so that only a single increase or decrease command from the controller is present at any one time. When engine speed is within the established deadband there is no signal to either solenoid valve, and the actuator position remains fixed. Should engine speed decrease below the edge of the established deadband, however, the controller automatically supplies a signal to the increase solenoid valve which then causes the actuator to move in the proper direction to unload the engine and increase speed. The signal to the solenoid valve disappears as soon as the speed moves back inside the established deadband and the actuator then remains stationary in its new position. Correspondingly, if engine speed increases beyond the established deadband, the controller provides the necessary signal to the decrease solenoid valve, which in turn moves the actuator in the necessary direction to increase engine loading and return the speed to within the deadband.

Single speed floating control has many advantages over a proportioning type of control for this application. Full automatic reset action is obtained to compensate for load change. This means that the actuator may assume any position in its entire range to satisfy the requirements of maintaining engine speed at the set point through the full range of vehicle loading, consistent however, with the available engine power. The width of the deadband in a floating control process normally is established on the basis of the required input measuring* lag together with the response time of the process. In general the greater the measurement lag and the slower the response of the process, the wider the necessary deadband. For this control system, however, the measurement lag is essentially zero and the response time of the process relatively small, being only that required to move the actuator. The response of the transmission will be almost instantaneous. The deadband required conceivably is quite small so that engine speed can be maintained very accurately.

The electronic controller is an all digital system receiving its input signals from the ring gear teeth on the engine flywheel and supplying command signals to the pair of solenoid valves which control the transmission actuator. This system was selected by the author

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* "A change in the measured variable is not instantly detected by the measuring means of any controller. That is, all controllers indicate what the controlled variable was, not what it is. Thus, we say that the controller has measuring lag." [7]

instead of an analog system, in order that good long term stability could be obtained over a period of ten years or more. This is not unusual life for a heavy-duty truck. Referring to the block diagram of the system shown in Figure 10, high frequency pulses from a crystal controlled time base are gated by the speed signals from the flywheel pickup and fed to a binary counter. The counter provides a binary number which is proportional to the period of the signal from the engine speed sensor. The binary number is fed into the comparator where it is compared with a preprogrammed set point. If the number is greater than the set point, this indicates an engine speed which is lower than required, and an appropriate signal is fed to the increase solenoid valve. The decrease solenoid valve is actuated when the binary number from the counter is less than the set point. A latch is positioned between the outputs of the comparator and the solenoid drivers to store the valve command signals during the interval that pulses are gated into the counter. This assures that each command signal is the result of a complete count. The fixed dead-band between increase and decrease signals to the valves is obtained by arranging for the comparator to ignore a fixed number of lower order bits from the counter. This technique permits obtaining two accurately established

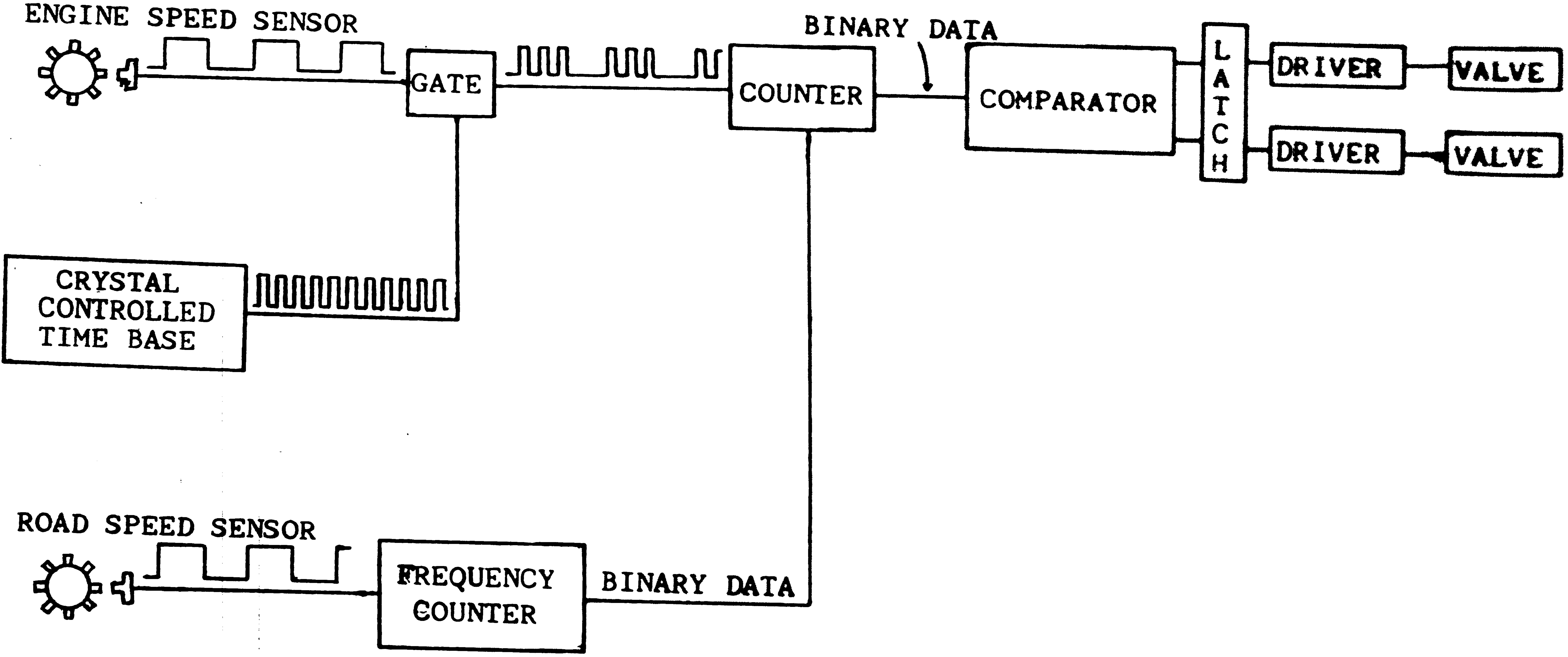

FIGURE 10 ENGINE SPEED CONTROLLER

set points, one at the high edge of the deadband and the other at the low edge of the deadband. Both points are obtained through the input of only a single set point to the comparator.

Previously mentioned was the requirement that engine speed be permitted to return to idle as the vehicle is brought to a halt. This reduction in engine speed is at a rate shown in the plot of engine speed in Figure 4. This function is accomplished by presetting the counter with a binary number which is proportional to the road speed of the vehicle. The smaller the preset binary number, the higher the required count before the set point is reached, and the greater the length of the required period indicating a slower engine speed. The preset binary number is limited to a maximum value which corresponds to an engine speed of 1700 RPM. This is accomplished by means of the frequency counter which is programmed to stop counting at this maximum value regardless of input frequency. The slope of the initial portion of the engine speed curve of Figure 4 is a function of the time base of the frequency counter. A shorter time base requires a higher input frequency and thus a higher road speed to reach the maximum count.

A maximum speed governor operating independently of the engine speed controller should be provided to prevent accidental engine runaway in the event of a malfunction which would prevent loading the engine through the transmission. This emergency device can assume the form of an air intake shutoff butterfly valve which is tripped from a backup electronic speed switch.

ROAD SPEED CONTROLLER

The road speed controller receives its command signal from the accelerator pedal and positions the injection pump fuel rack as required to maintain a given road speed with the controlled 1700 RPM engine speed. Each position of the accelerator pedal commands a definite road speed. A modified single speed floating control system is used to position the injection pump fuel rack through a pneumatic actuator controlled by a pair of solenoid valves. A normally-closed valve is used for "increase" while a normally-open valve is used to dump air from the cylinder for "decrease". This arrangement provides a fail-safe operation and also permits stopping the engine by simply turning-off the "RUN" switch. De-energizing these valves automatically returns the injection pump rack to the no-fuel position.

The requirements of the road speed controller are more difficult to meet than those of the engine speed controller previously described. The response time of the controlled process is greater. As the fuel rack of the injection pump is changed in position, a certain elapsed time is required before the resulting road speed change can be detected. The mass of the entire vehicle must be accelerated or decellerated before a change in the road speed can be noted. Unless the deadband of the controller is reasonably wide, this process lag could produce overshooting of the set point. The rack actuator would continue to move in the direction to correct road speed so long as the measurement remained outside of the established measurement deadband. Overcorrection of the rack position would result.

A rate-of-approach feature has been added to the floating control system to compensate for this process response lag. This feature provides for positioning the control actuator such that the vehicle accelerates or decelerates toward the set point speed at a constant rate. This constant rate of acceleration is lower than that which would result from normal control action and is maintained only within a certain distance from the deadband. In Figure 11 these upper and lower approach bands of constant acceleration are shown. As the speed enters the approach band minor cycling occurs before the optimum setting of the throttle is obtained. This cycling determines the design width of the approach bands. By proper design, the rate of acceleration can be chosen

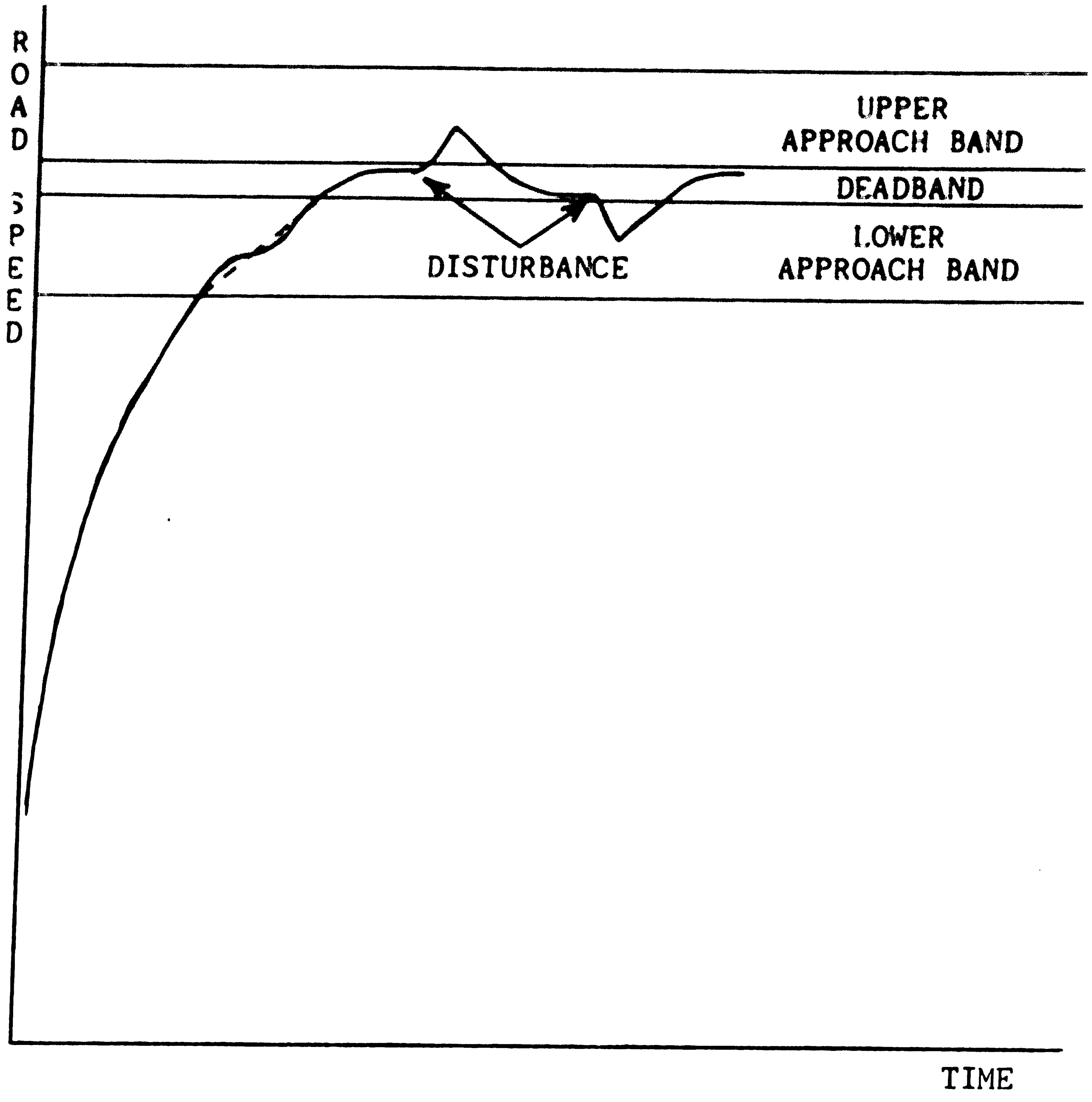

FIGURE 11 ROAD SPEED CURVE

so that in effect the measured variable will coast into the deadband. Without the rate of approach feature, motion of the actuator would be at a fixed rate until the measurement had entered the deadband. Because of the process lag, the measured value conceivably would coast completely through the deadband and require a correction in the reverse direction. Thus a hunting condition would result.

A block diagram of the road speed controller is shown in Figure 12. A series of pulses from the road speed sensor control a gate which feeds high frequency pulses from a time base into the counter. This is similar to the arrangement used in the engine speed controller. In this case, however, the frequency of the time base is controlled by the accelerator pedal of the vehicle. The counter will reach a specific count in a time which is determined by the frequency of the variable time base as determined by the position of the accelerator pedal. With this arrangement, a given count may be obtained over the full range of vehicle road speed.

As previously described, the road speed control system acts to maintain the vehicle speed within a narrow deadband surrounding the set point established by the accelerator pedal. High and low approach bands,

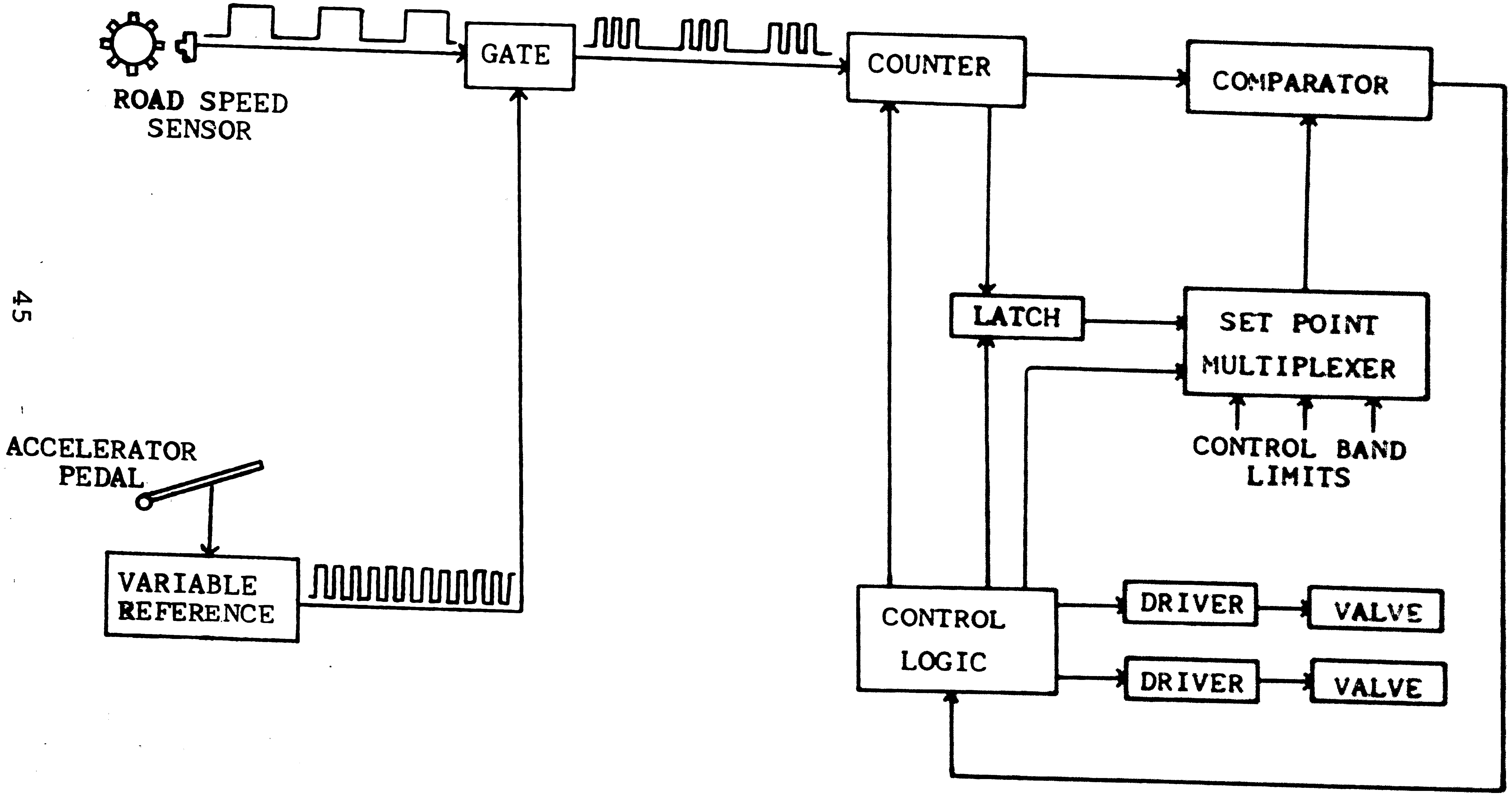

FIGURE 12 ROAD SPEED CONTROLLER

several times the width of the deadband, extend above and below the deadband. It should be remembered that the set point, which is located at the center of the deadband, is movable throughout the entire road speed range of the vehicle and that the relationship between this set point and the approach bands above and below the deadband is fixed over this entire range. Movement of the set point through the range is achieved by means of the variable time base. The fixed relationship between the two approach bands and the deadband exists because the comparator is continually looking for the same four limits at the output of the counter. These correspond to the extremes of the deadband and the two approach bands.

The output from the comparator is fed to the control logic which drives the increase and decrease solenoid valves. Whenever the road speed is within the deadband neither solenoid valve is energized since a control correction is not required. A set point multiplexer permits the comparator to determine the relationship of the measured road speed to the set point and to the limits of the two approach bands. Whenever the measured road speed is outside of the deadband, but within either the high or low approach band, the appropriate solenoid valve is operated so as to bring the vehicle speed back toward the deadband at a rate which avoids overshooting the deadband. The rate of return to the set point is controlled by comparing an instantaneous value of road speed to an intermediate set point. This set point has been computed from the previously measured value of road speed, so as to maintain the constant rate of speed change. To maintain the desired rate, the new set point, as computed at the end of each measurement interval, is obtained by adding to or subtracting from the present value of road speed, a fixed number of counts. Updated values of set point are successively stored in the latch and fed to the comparator via the set point multiplexer. The control of all functions in the system is through the control logic.

The sequence of events is as follows: During the interval in which the input to the counter from the gate is low, which corresponds to the space between road speed sensor pulses, the control logic directs the multiplexer to feed the value of the set point into the comparator. The comparator produces a signal indicating above, below, or within the deadband. If the measurement is within the deadband, then both solenoid valves are off. If the measurement is above or below the deadband, the multiplexer sends upper or lower approach bands limits to the comparator. The comparator then indicates whether the signal is within or outside of the approach band. If the measured value is outside of the approach band, then the proper solenoid valve is turned on full. If the measurement is within the approach band, the multiplexer will feed the computed value of the new set point, which has been stored in the latch, to the comparator. The comparator then indicates any deviation from this set point and turns on either solenoid valve in order to effect the necessary correction. The next set point speed value then is computed by causing the counter to count up or down a fixed number of counts depending on whether the current speed is below or above the deadband. This new set point value then is stored in the latch. The counter is reset and then is ready to count a new series of pulses from the variable time base.

The rate-of-approach feature of this control system should make accurate road speed control possible without any tendency toward hunting. An actual installation will be necessary to determine the width of the deadband, the width of the approach band, and the actual rate-of-approach to be used. It is conceivable that a single rate-of-approach may not be suitable to handle all conditions of load on a given vehicle and a type of derivative action control may be a necessary addition. A modification of the rate-of-approach circuit would be necessary such that the actual rate-of-approach is determined by the rate of deviation of the controlled variable from the set point.

As previously mentioned, two forward drive speed ranges are provided, "drive low" and "drive high". A fixed road speed ratio of ten to one exists between "drive low" and "drive high". The range determining components of the engine speed control circuitry of Figure 10 have been selected to provide the "drive low" range. The "drive high" range is obtained by dividing the input frequency from the engine speed sensor by 10. This requires the vehicle to move ten times as fast to provide the same input frequency to the gate.

OPERATION AT ZERO ROAD SPEED

At zero road speed the normal engine speed controller cannot be used because its operation is to control engine speed by the application of load, but at zero road speed there is no load. Therefore, at zero road speed the output from the engine speed controller is transferred from positioning of the control lever of the pumps in the transmission to positioning of the fuel injection pump rack of the engine. This mode of operation is used in both the "neutral" and "start" position.

The relationship of the zero road speed control to the total system is shown in Figure 13. As previously described, in "drive" and "reverse" engine speed is controlled by positioning the control lever for the pump/motors in the transmission and road speed is controlled by positioning the fuel injection pump rack. In "neutral" and "start" the engine speed is controlled by positioning the fuel injection pump rack. In "neutral" and "start" the input to the frequency counter of the engine speed control shown in Figure 9 comes from the variable reference rather than the road speed sensor. This allows the engine speed to be governed in the range between idle and 1700 RPM by use of the accelerator pedal. This is used when starting the engine or when operating accessories from the power-take-off, as for example, driving a blower for unloading dry bulk or driving the barrel of a ready-mix truck. The road speed controller assumes control of the entire system while bringing the vehicle to a stop. At zero road speed the transmission is shifted to neutral and the engine speed control output is shifted to the fuel injection pump rack.

A typical sequence of operations is as follows.

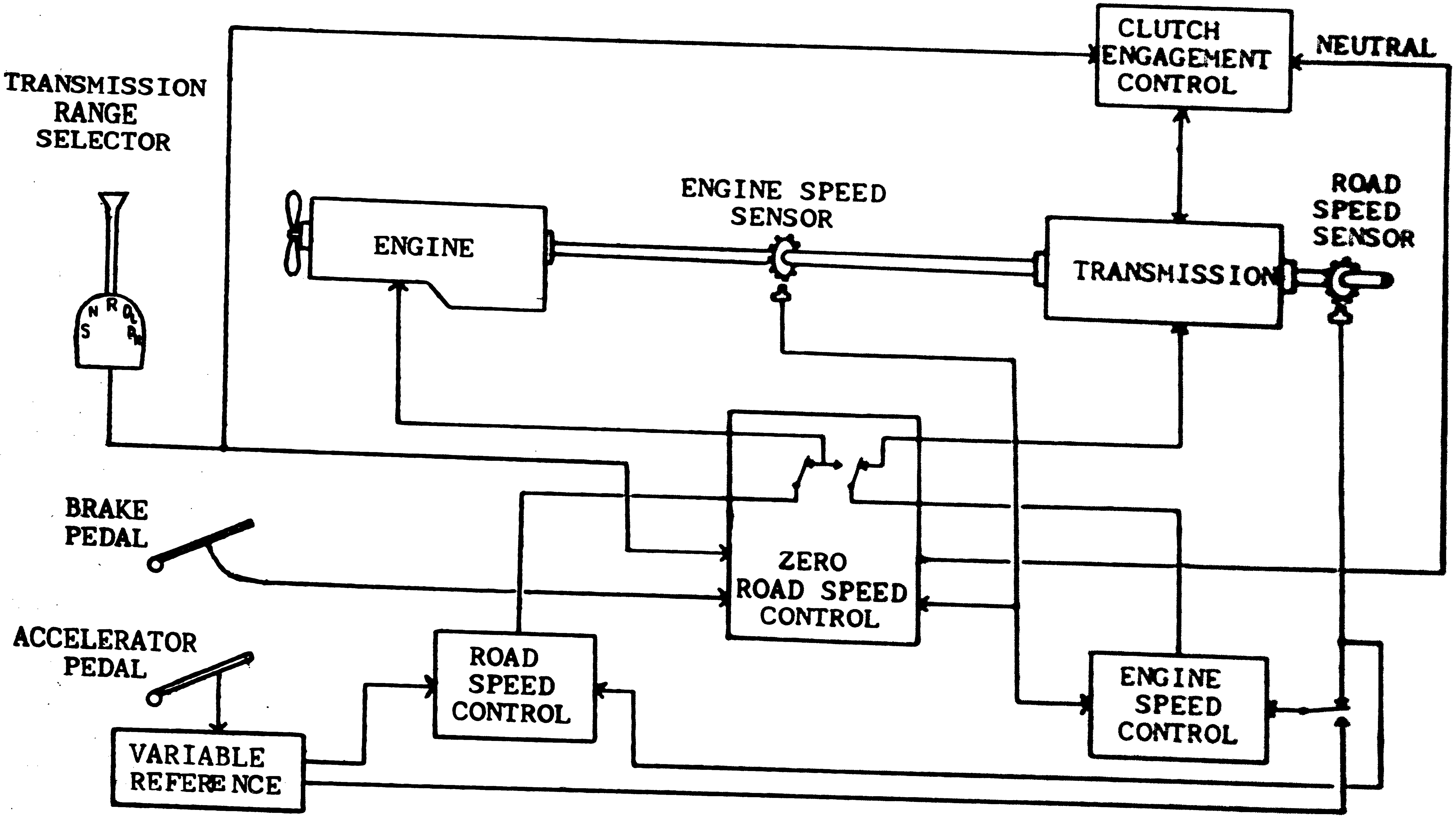

FIGURE 13 BLOCK DIAGRAM OF THE ENTIRE SYSTEM

To bring the vehicle to a halt, the driver removes his foot from the accelerator pedal. This calls for minimum road speed and therefore the road speed controller cuts back the fuel injection pump rack to the minimum fuel position. With no fuel supplied to the engine, the vehicle decelerates to a point where the driver makes a brake application to bring the vehicle to a complete halt. With application of the brake, the zero road speed controller enters the picture and maintains the injection pump rack in the zero fuel position. As the vehicle decelerates from the initial release of the accelerator pedal and during brake application, the engine speed controller continuously varies the transmission ratio so as to maintain engine speed while the vehicle is driving the engine. Eventually a point is reached where the road speed drops so low that engine speed cannot be maintained. At this point the road speed will be very low and the engine speed, as shown in Figure 4, will be close to idle. As engine speed starts to drop below idle, the zero road speed control will shift the transmission into neutral and will electronically switch the output of the engine speed contoller to the fuel injection pump rack of the engine. The engine speed control will return the rack to the proper position to maintain engine speed at idle.

The engine flywheel maintains engine speed for the fraction of a second required for the electronic switching and the movement of the rack.

To start the vehicle moving forward again the driver removes his foot from the brake pedal. This reengages the proper clutches in the transmission, reconnects the engine speed control output to the control lever for the hydraulic units in the transmission, and connects the output of the road speed controller to the fuel injection pump rack of the engine. The vehicle then will try to maintain whatever speed the accelerator pedal calls for. The ability to make smooth starts is a feature of this control system. This is because the road speed controller automatically is positioned for zero road speed when the vehicle is brought to a halt. If the vehicle is to remain in the stopped position without the brake pedal being continuously depressed the transmission can be shifted into neutral. An inherent feature of this system is that it provides an automatic interlock which returns the fuel injec~~tion pump~~ rack to the minimum fuel position whenever the brake pedal is depressed.

CHAPTER 5 - ADAPTING TO THE ENVIRONMENT

THE AUTOMOTIVE ENVIRONMENT

Electronic equipment installed on automotive vehicles is subject to a complex, hostile environment made up of various components. In the climatic area these items are temperature, humidity, immersion, salt spray, dust, oil and grease, gravel bombardment and altitude. In the dynamic area are shock and vibration. In the electrical area we have power line anomalies and external electric and magnetic fields. If we consider these individually as they relate to the electronics of the control system proposed for the MAPT it will be seen that certain items can be eliminated through proper design, proper packaging and proper placement of the electronic package on the vehicle. If the electronics package is located within the cab of the truck, for instance, we automatically eliminate items such as gravel bombardment, salt spray and immersion. By proper packaging of the electronics in a sealed box we can eliminate the effects of dust, oil and humidity. By proper location and mounting we can minimize the shock and vibration. Temperature, however, is one of the most severe environmental considerations for vehicle electronics. A feature article in the January 1974 issue of Automotive Engineering entitled "How Tough is the Environment for Auto Electronics?" pretty well spells out the problems of the temperature environment on board vehicles.

> "Temperature is one of the most severe environmental considerations for vehicle electronics. High-volume manufacturing techniques make it virtually imperative that all vehicles be built for every extreme. Tests at cold-weather sites indicate that -40 F is the lowest temperature that can be reasonably expected in a parked vehicle. Since temperature rise is slow after the vehicle is started at such an extreme, this temperature is also recommended as the low soak standard. An electronic system should, in addition, be able to withstand storage at temperatures to -60 F.
>
> "At the other temperature extreme, values will vary with location in the vehicle. Chassis components can see 185 F to 250 F, depending on their proximity to such vehicle heat sources as exhaust, transmission, and brakes. Direct exposure to transmission, hydraulic or axle oils requires tolerance to 350 F. Components mounted on the exterior of the vehicle experience temperatures to 185 F. This limit also applies to interior 'B' pillars, doors and floor. The top of the instrument panel and the rear package shelf can reach 235 F and temperatures behind the instrument panel reach 178 F.
>
> Extreme underhood temperatures
>
> "Underhood temperatures are particularly critical because the engine and its associated controls and accessories offer the most fertile area for electronics systems, sensors and actuators. Generally, components reasonably isolated from the engine and exhaust manifold reach temperatures to 250 F. But minor changes in location can result in

> radical shifts in temperature exposure. These values have been recorded: engine and transmission oil 300 F, choke housing 400 F, exhaust manifold surface 1200 F, and gas within exhaust manifold 1500 F."

Electrical Environment and Noise Immunity

The hostile environment, encountered by electronic equipment which results from electrical interference on vehicles, is described in the literature.[8,9] The largest negative transient on the vehicle supply line is 100V. Load dump transients are positive and as large as 120V. The manner in which unwanted signals are introduced into the electrical system of the vehicle has been researched and is covered in a section of reference number 10. According to this reference, there are three coupling methods: Magnetic coupling, capacitive coupling, and conductive coupling.

The inherent noise immunity of CMOS logic is greater than that of TTL but this is not of substantial significance in our case inasmuch as the electronic package will be completely enclosed in a housing fabricated of sheet steel. Sheet steel is used because "a steel box will absorb radiated energy at 150 kHz such that any signal inside the box is reduced 12.9 dB per mill of thickness of the box. In other words, a 1/16 inch thick steel box will attenuate radiated interference by over 800 dB. A similar aluminum box will attenuate 1 dB per mill or 62.5 dB total." [11] Thus, it is highly unlikely that radiated energy will affect the circuitry.

Interfering signals then can enter the control circuitry only through the input leads entering the sheet metal housing. Noise on the power supply leads is effectively eliminated by a low pass filter at the input. In order to minimize the pickup of unwanted signals on the sensor leads, ungrounded two-wire conductors are used to connect each magnetic transducer to its input circuit in the control box. This practice eliminates conductive pickup by leaving the sensor terminals ungrounded and connecting one of the two sensor leads to a common point inside the control box. To eliminate the possibility of inductive or magnetic pickup, these two leads from each sensor will be a twisted pair. Further treatment to eliminate magnetic pickup consists of running all sensor leads together inside flexible steel conduit. A good choice for the sensor leads consists of a cable containing multiple twisted pairs and an external braided metal shield. This cable is commercially available and provides additional protection by eliminating capacitive pickup. To reduce the vulnerability of the input circuits of the system to false triggering, Schmitt triggers are used as previously described.

CHAPTER 6 - SPEED SENSORS

For the digital system proposed, sensors which produce a series of pulses whose number is proportional to speed are the most convenient type. This digital type of transducer is available in either optical or magnetic form. Recently optical systems have been developed which consist of an LED light source and a phototransistor receiver. Periodic interruption of the transmitted light from the source to the transducer produces output pulses from the system. This type of sensing device has been ruled out in this system, however, because of problems which would result from the accumulation of dust and dirt, either on the light source or on the receiver.

Magnetic transducers are available in several forms. One of these is the magnetically operated reed switch in which moving mechanical contacts are actuated from the magnetic circuit. This device has limitations of life and therefore is not satisfactory for high speed operation. Attempted use of the reed switch transducer for electric speedometers has verified this contention of short life.

Instead, it was decided to use a static type of magnetic transducer which involves no moving parts and assures long term stability and long life without any mechanical wear out. The common variety of magnetic transducer operates on the inductive principle; a permanent magnet is surrounded by a coil of wire such that changes in the external field of the magnet cause a current to be induced in the coil. When this device is mounted in close proximity to the face of a gear, electrical pulses will be induced in the coil as each tooth passes the transducer. The magnitude of the voltage pulses induced in the coil is dependent upon several factors such as the magnitude of the variation of the magnetic flux passing through the coil and the number of turns on the coil. The magnitude of the voltage is also dependent upon the rate of change of the magnetic flux. This means that the output signal from the coil will be of a greater magnitude at high rotational speeds of the gear than at low speeds. The output amplitude from this type of transducer is not a linear function with speed and consequently there is a minimum speed at which this device is usable. The output signal from an inductive type magnetic transducer is essentially a sign wave with both positive and negative components.

The second type of magnetic transducer operates on the Hall effect principle. The Hall effect produces usable voltages across the edges of certain current carrying electrical conductors when a magnetic field is applied perpendicular to the flat side of the conductor. If the current flow through the element is maintained constant and the magnetic flux density, B, is varied, the Hall voltage is proportional to this flux density.[12] Magnetic transducers using the Hall effect principle are designed to produce a nominal square wave output signal and, most importantly, will operate down to zero speed. As is the case with any semiconductor type device, however, there is a definite temperature limitation involved in the operation of a Hall effect device. For many of these devices this limit is 220° F. The vendor, however, indicates that work is in progress to extend this temperature limit upwards.

In order to avail ourselves of the advantages of the two types of magnetic transducer, it is likely that a combination of the two types would be used in this system. Because of the higher temperature capability, the inductive type transducer would be used inside the transmission for measurement of the shaft speeds controlling clutch engagement. In this location the reduced output of the inductive type transducer at low speeds will not be a handicap. A typical transducer will produce over 5 volts peak to peak at 200 pulses per second with a 0.02 inch air-gap. As can be seen from Figure 4, member C_2 is the member of the transmission whose speed first drops low enough to cause problems. However, it is necessary to know the shaft speeds only at the shift points. At these points, the speeds of all the members are high enough so that they do not present a problem in the form of low output.

The Hall effect sensor, however, would be used for the measurement of road speed because it is usable down to zero speed. This unit would be mounted at the rear bearing cover of the transmission. The sensor for engine speed measurement could be either the inductive type transducer or the Hall effect type with preference being on the side of the Hall effect unit due to its nominal square wave output. The chief advantage of the nominal square wave output signal results from its noise immunity. Pulses from the sensor are fed to a Schmitt trigger. Triggering occurs at a given voltage level of the input pulse. The nominal square wave presents a signal with a relatively short rise time as compared to a corresponding signal of sine wave form. Therefore, when noise is superimposed on the two signals it is obvious that the shift in triggering point of the square wave will not change significantly whereas the trigger point of the sine wave may shift appreciably depending upon the magnitude of the noise. This shift in triggering point would affect measurement of period, hence greater speed measurement accuracy is possible with the square wave signal.

CHAPTER 7 SELECTION OF LOGIC TYPE

There are many families of digital integrated circuit logic available today. After careful study of the characteristics of these logic families, all but three were rejected for possible use in this system. These three types of logic are TTL, CMOS and PMOS. The most severe requirement for the logic type is the temperature range over which the system must operate. As stated previously, the system must be able to operate down to -40°F. Both the military and commercial versions of CMOS can operate down to at least -40°F. However, only the military version of TTL can operate down to -40°F. Therefore, if TTL logic is employed in the system, it will be necessary to use the more expensive military version, or to provide a heater. Certain PMOS which can operate down to -40°F is available. However, it will most likely cost more than standard PMOS.

The upper temperature limit for a device located behind the instrument panel is 178°F. Again, this is outside the 32°F to 167°F range of the industrial version of TTL. Therefore, if TTL is employed in the system, the military version must be used regardless of whether or not a heater is used. The commercial version of CMOS can operate over the temperature range of -40°F to 185°F and therefore it is not necessary to use the more expensive military version if CMOS is employed in the system.

Power dissipation is another important factor. Because of their low power dissipation which results in low generated heat, CMOS and PMOS integrated circuit packages can be mounted close together on printed circuit boards. A small package housing the complete electronic assembly thus becomes possible, which minimizes the problem of finding sufficient space to mount the package behind the instrument panel of the vehicle. The high dissipation of TTL logic necessitates less dense packaging or forced air cooling. Also this power dissipation limits the number of gates which can be put into a single integrated circuit package.

After a final design for the complete system has been established it may be desirable to consider large scale integration in which the entire digital circuitry could be included on one or two integrated circuit chips. The resulting advantages are smaller physical size, reduced cost, increased reliability and easier repair. With large scale integration (LSI), circuitry equivalent to thousands of transistors may be included in a minimal package size. Once tooled, the cost of the LSI circuit would be only a fraction of the cost of the original circuit components. One semiconductor manufacturer indicates that, at the volume expected, the cost of implementing this system with CMOS LSI would be 25% of using standard CMOS integrated circuits. Reduced size of the package also contributes to lower cost. With integrated circuits, failures usually occur at the point where external leads connect to internal circuitry. With LSI many individual integrated circuits are combined on a single silicon chip, thus eliminating a large number of external interconnections between individual integrated circuits. This reduction of connections between the internal circuitry and the external leads results in improved reliability. Should servicing become necessary, the reduction in the number of packages simplifies the decision concerning which component should be replaced. CMOS and PMOS also contribute to the overall reliability of the system because of their lower power dissipation which results in lower operating temperature of the overall system.

Power dissipation and supply voltage combined determine the complexity of the power supply. TTL requires 5 V ± 10% at several amperes which requires a series pass or switching type voltage regulator circuit. This voltage regulator also must operate over the $-40^{\circ}F$ to $178^{\circ}F$ temperature range. The common commercially available integrated circuit type voltage regulator device will not operate over this temperature range and therefore a special device would be required. Provision must be made in the design of the power supply to block out high voltage transients originating in other parts of the vehicle electrical system. Otherwise, these transients could damage the solid state components of the electronic system. A zener diode commonly is used as a clamp to eliminate these incoming spikes and prevent their being passed through the power supply. The zener diode clamp operates in conjunction with a resistor in series with the power supply. The high current requirement of the TTL logic necessitates a relatively low value of the series resistor which requires the use of a zener diode with high current capability at increased cost.

PMOS is not commercially available in IC devices of the type required for this system, but is commonly used in large scale integration (LSI). It would be expected from individual gate dissipation that the power supply requirements for PMOS LSI for this system would consist of 12V at approximately 100 ma and possibly a negative supply.

CMOS can operate anywhere between 3 and 15 volts and would require only 20 ma when applied to this system. This wide supply voltage range allows CMOS to be run directly from the vehicle electrical system with only a low current zener clipper to protect the CMOS from high supply voltage due to failure of the alternator voltage regulator or from high voltage transients. This simple power supply requirement makes the choice of CMOS attractive from a cost standpoint.

CMOS with its characteristic slower speed operation and higher power supply voltage has greater noise immunity than TTL. The lower speed of CMOS also eliminates some of the problems experienced with TTL in the form of crosstalk due to its higher switching speed. More careful circuit layout and additional bypassing are necessary to eliminate these effects. Because of these various considerations (lower cost, wider temperature range, lower power dissipation, LSI capability and smaller overall package), CMOS is heavily favored as a logic choice for the circuitry of this system with a possible consideration of PMOS if large scale integration is to be considered.

CHAPTER 8 - CIRCUIT DESCRIPTION

In this chapter circuitry which can implement the previously discussed control system is presented. This circuitry is subdivided into several parts. The first of which is the power supply. The next part is the clutch engagement control electronics. This circuit decides which clutches should be engaged according to the position of the selector lever. The third part, the clutch engagement verification circuit, verifies the fact that the two clutch halves are at the proper speed to be engaged. The next part of the control system is the clutch speed comparison circuit. This circuit compares the speeds of the two halves of the next clutch to be engaged and sends a signal back to the clutch engagement circuitry when the speed of the two halves is the same. This circuit is used also to detect zero road speed. This check is made when a shift from "neutral" to "drive" or "reverse" is called for. The last two parts of the circuitry are the engine speed control circuit and the road speed control circuit.

Throughout this chapter, all leads indicated by "POS" or "NEG" are connected to the positive or negative vehicle supply. All flip-flops are D flip-flops, type MC14013.

Power Supply

The power supply circuitry appears in Figure 14. The dc supply for the digital logic includes provision for removing transients from the vehicle electrical system and clipping the output to a maximum of 15 volts. The clipping is performed by an 11.5 V ± 5% zener diode in conjunction with a ten watt 100 ohm resistor. The two ohm internal impedance of the zener diode gives an additional 2.4 volts across the zener diode in the presence of load dump transients which may be as high as 120 volts.[9] The five percent tolerance on the zener diode voltage combined with the temperature coefficient of 0.07% /^{o}C add another 9% or 1.035 volts to the voltage of the zener diode. Thus, altogether the voltage across the zener diode, and therefore the output of the power supply, is kept below 15 volts. The 1N4004 diode blocks

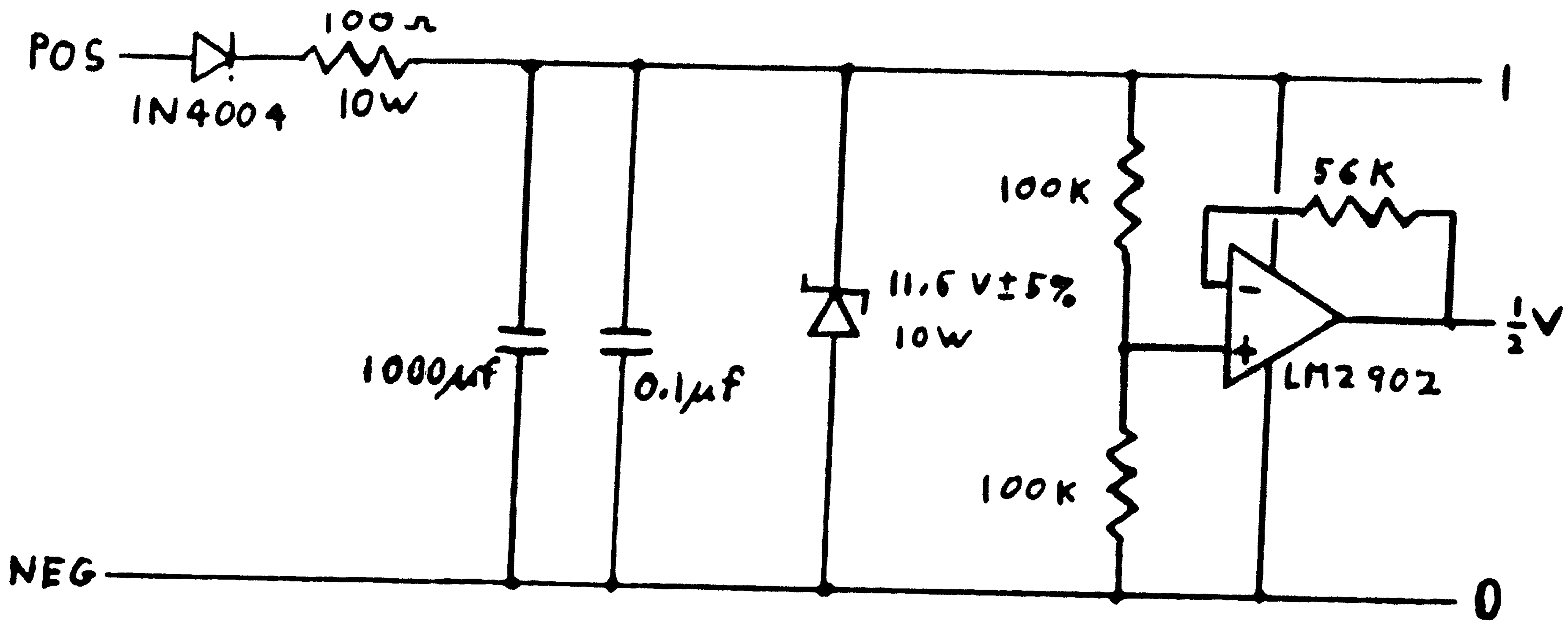

FIGURE 14 POWER SUPPLY CIRCUIT

negative transients. Although the largest transients are in the 100 volt range, the extra protection afforded by the 400 volt rating of this diode is worth the slight increase in cost. The 1000 microfared capacitor supplies current to keep the circuit operating for the short duration of the negative transient. The 0.1 microfared capacitor is used to provide high frequency bypassing. The remainder of the components in this circuit are used to provide a bias voltage for the Schmitt triggers. This bias voltage is one half the supply voltage and labeled ½V.

Clutch Engagement Control Circuit

As mentioned previously, this circuit controls the engagement of the six clutches in the transmission. These six clutches must be engaged in the proper order at the proper time. A schematic diagram of this circuit appears in Figure 15. Briefly, the circuit operates as follows. The position of the selector switch indicates which range is desired. This information is stored in four clocked flip-flops. These flip-flops are necessary so that if an improper shift selection is made the previous shift selection will be maintained. An improper shift will also sound an alarm. In "drive" the transmission can be in any one of four ranges. An up/down counter is used to keep track of which of these ranges the transmission is in. The outputs of the up/down counter are decoded to provide shift engagement signals. These signals are sent

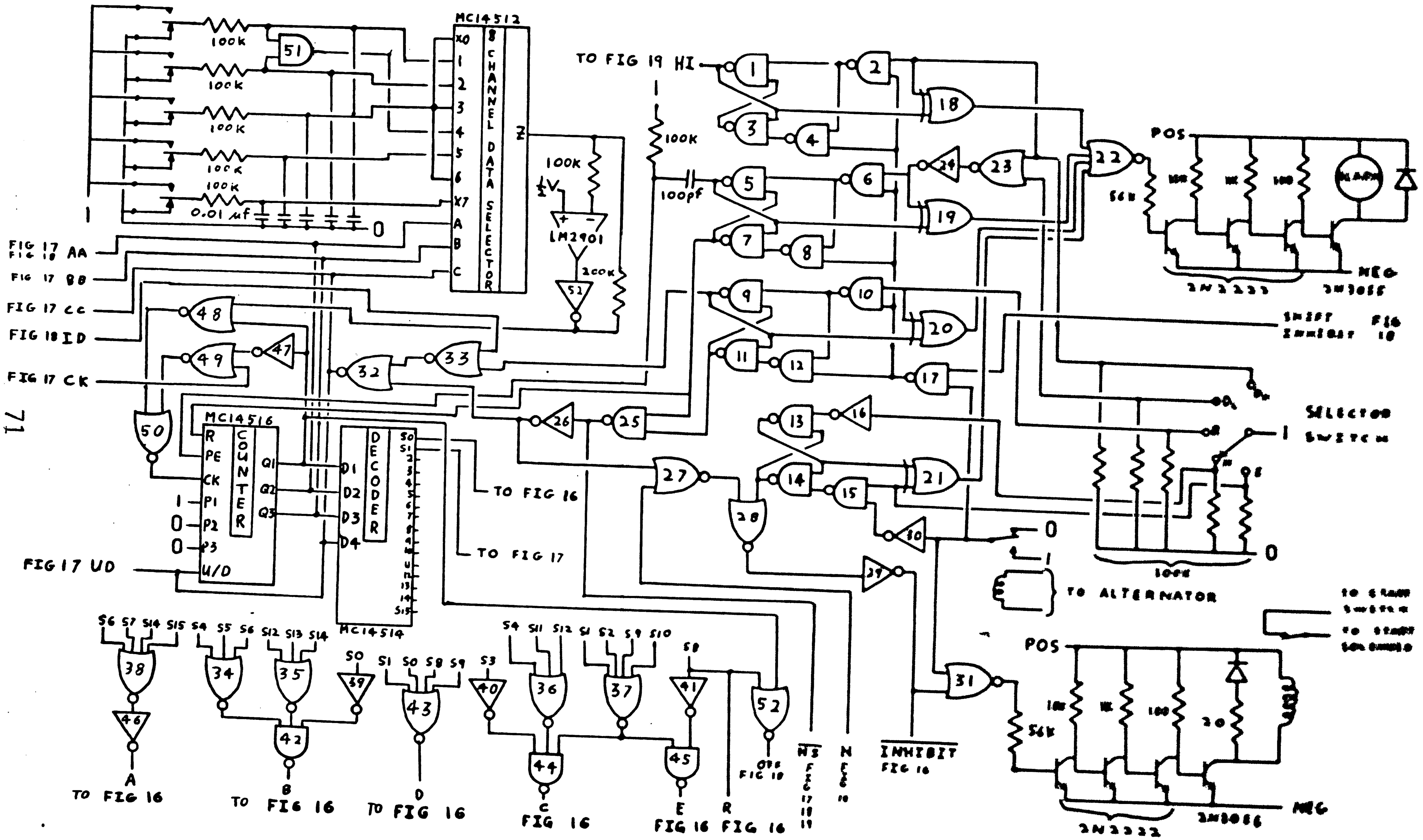

FIGURE 15 CLUTCH ENGAGEMENT CONTROL CIRCUIT

to the clutch engagement varification circuit to engage the clutches. To make sure that one clutch is engaged before another is disengaged, a signal from the pressure switches connected to the clutch hydraulic lines is used to clock the counter from the clutch engagement state to the clutch disengagement state.

A more detailed discription follows. The position of the selector switch determines the range ("start", "neutral", "reverse", "drive low" and "drive high") that the transmission is to be in. This switch may be mounted on the instrument panel in such a manner as to be inside the housing of the electronic circuitry or it may be mounted remotely. If it is mounted remotely it will be connected to the circuitry by the same type of cable as was previously described for use in connecting the sensors to the circuitry. Four clocked set-reset flip-flops (gates 1 through 15) are used to store the information from the selector switch. Gate 17 provides the clock input for the first three flip-flops (gates 1 through 12). The clock for the fourth flip-flop will be discussed later. When either of the inputs to gate 17 is low, the states of the flip-flops can be changed. The shift inhibit input is high both when the truck is moving or when the engine is not at idle. This input is provided by another circuit and will be described later.

The other input to gate 17 comes from a relay. This relay pulls in and provides a high output whenever the engine turns the alternator faster than cranking speed. The use of a relay of this type to disengage the cranking motor once the engine has started is commonplace and is known as the Delco-Remy "ADLO" system. Therefore, use of a relay in this application will present no problem. Thus, whenever the engine is not running, or when it is running at idle speed and the vehicle is not moving, the state of the first three flip-flops can be changed by the selector switch.

When the engine is running at some speed other than idle and/or the vehicle is moving, changing the selector lever will not change the state of the flip-flops but will sound the alarm. The signal to turn on the alarm comes from one of the EXCLUSIVE-OR gates 18, 19, 20 or21. If the input to any of the flip-flops does not agree with the output of that flip-flop, due to the input having been changed when the clock input was low, the EXCLUSIVE-OR gate for that flip-flop will turn on the alarm through NAND gate 22. The driver for the alarm consists of four transistors in common emitter configuration. Each transistor is either in saturation or cutoff. Only the last transistor (2N3055) will ever see a voltage higher than 2 volts. Therefore, high voltage transients will not hurt these transistors. The choice of 2N2222 transistors for the drivers and a 2N3055 transistor for the output was based on the wide availability and low cost of these transistors. The alarm consists of a buzzer and light similar to those presently used for low air indication except that the buzzer will have a different tone. The diode supresses any inductive kick-back from this buzzer. Because the 2N3055 is not a high speed transistor, this diode need not be a high speed device.

The flip-flop made up of gates 13,14 and 15 is the neutral-start flip-flop. When the selector lever is not in "drive" or "reverse", the output from this flip-flop determines whether the transmission is in "neutral" or "start". Once the engine has started, gate 15 inhibits the flip-flop from going into "start". However, if the flip-flop is in "start" it will stay there until put into "neutral". This allows a shift into "start" only when the engine is not running, but from "start" to "neutral" anytime.

With the selector switch in "drive high" the outputs of gates 1 and 5 are high and the outputs of gates 3 and 7 are low. With the selector switch in "drive high" the outputs of gates 1 and 5 are high and the outputs of gates 3 and 7 are low. With the selector switch in "drive low" the outputs of gates 3 and 5 are high and the outputs of gates 1 and 7 are low. Thus the second flip-flop is used to indicate "drive", with the first flip-flop indicating "drive high" or "drive low". The third flip-flop indicates "reverse" and the fourth flip-flop indicates "neutral" or "start".

The starter interrupt feature of this circuit allows the starter motor to be energized only when the engine is not running and the transmission is in "neutral". This interlock uses a relay whose contacts are in series with the starter switch and the starter solenoid. The driver for the relay is the same type as that for the alarm. However, the protection diode has a resistor in series with it. This allows the relay to drop out faster than it would if only the diode were used. This resistor has the same resistance as the relay coil. This allows the voltage across the driver transistor to go to twice the supply voltage. The $\overline{\text{INHIBIT}}$ output goes low when the transmission is in "neutral". With this output low and the output of the engine run relay low, the starter interlock relay is de-energized and the starter is allowed to crank.

The clutches engaged in the various ranges are shown in Table 1. The only difficult range is "drive" which comprises four separate ranges. To keep track of which range the transmission is in, an up/down counter is used. This counter is counted up or down one count every time the two halves of the next clutch to be engaged are at the same speed. The outputs of the counter are decoded

TRANSMISSION RANGE	CLUTCHES						SELECTOR SWITCH
	A	B	C	D	E	R	
START		ON					START
REVERSE					ON	ON	REVERSE
I			ON		ON		DRIVE LOW
I			ON		ON		DRIVE HIGH
II			ON	ON			
III		ON		ON			
IV	ON			ON			
NEUTRAL							NEUTRAL

TABLE 1 CLUTCHES ENGAGED IN THE VARIOUS RANGES

by the decoder and gates 34 through 46 to give clutch engage signals. These signals go to the clutch engagement verification circuit where a second, less accurate check of clutch half speeds is made. If this check also indicates that the clutch should be engaged, then the proper solenoid valve is turned on.

Table 2 shows the relationship between the counter output, transmission range, the clutches engaged and the members whose speeds are compared. As can be seen, there is one count between each of the four ranges of "drive high". This is due to the fact that the new clutch is engaged before the old clutch is disengaged. This keeps the engine under load in the event that one of the clutches does not engage. To insure that the new clutch is engaged, an oil pressure switch is installed in the hydraulic fluid line of the clutch. A signal is then required from this switch before the counter is advanced and the old clutch is disengaged.

This is accomplished as follows. Whenever the selector switch is not in drive, the output of gate 7 is high. This resets the counter to 000. As seen in Table 2 this is the count for "reverse", "neutral" or "start". If the selector switch is in "reverse" then the output of gate 9 is high which forces the output of gate 32 high. This

	INCREASE					DECREASE			
COUNTER OUTPUT	CLUTCH TO BE ENGAGED OR DISENGAGED	DECODER OUTPUT	D3	MEMBERS TO BE COMPARED	RANGE	CLUTCH TO BE ENGAGED OR DISENGAGED	DECODER OUTPUT	D3	MEMBERS TO BE COMPARED
000	Eon, Ron	S8	1		$\overleftarrow{R}$ $\overrightarrow{N,S}$	Bon	S0	0	
001	Eon, Con	S9	1	$\textcircled{6} \le \textcircled{1}$	I	Doff,Con	S1	0	ROAD
010	Don	S10	1			Eon	S2	0	
011	Eoff	S11	1	$\textcircled{1} \le \textcircled{C_2}$	II	Boff	S3	0	$\textcircled{6} \le \textcircled{1}$
100	Bon	S12	1			Con	S4	0	
101	Coff	S13	1	$\textcircled{6} \le \textcircled{C_2}$	III	Aoff	S5	0	$\textcircled{nC_2} \le \frac{1}{2}\textcircled{6}$
110	Aon	S14	1			Bon	S6	0	
111	Boff	S15	1		IV		S7	0	$\textcircled{C_2} \le \textcircled{1}$

TABLE 2 RELATIONSHIP BETWEEN THE THE COUNTER OUTPUT, TRANSMISSION RANGE, CLUTCHES ENGAGED AND MEMBERS WHOSE SPEEDS ARE COMPARED

causes the decoder output S8 to go high. Gates 34 through 46 decode this signal and produce signals indicating that clutches $\boxed{E}$ and $\boxed{R}$ should be engaged. If the selector switch is in "neutral" or "start" the outputs of gates 7 and 11 are high and the output of gate 9 is low. This causes the outputs of gates 25 and 32 to go low and the decoder output SO goes high. If the selector switch is in "neutral", gates 14 and 27 will be low causing the $\overline{\text{INHIBIT}}$ output to go low. This puts the transmission in "neutral" by disabling the drivers for the solenoid valves which engage the clutches. If the selector switch is moved to "start" and the engine is not running, gate 14 will go high. This makes the $\overline{\text{INHIBIT}}$ output go high and allows the clutches to be engaged. With the decoder output SO high clutch $\boxed{B}$ will be engaged. This engagement takes place even if the clutch engagement verification circuit determines that because of clutch half speed mismatch it should not.

The only remaining range is "drive". The operation of the circuitry with the selector switch in this position is more complicated. With the selector switch in "drive" the output of gate 5 goes high and is coupled through the 100 pf capacitor into the preset enable (PE) input of the counter. This presets the counter 001. The 100,000 ohm resistor discharges the capacitor to a low level in approximately ten micro-seconds. With the preset enable input low, the counter will again respond to clock pulses. With the counter preset to 001, the transmission is in range I and clutches $\boxed{C}$ and $\boxed{E}$ are engaged. When the driver steps down on the accelerator, the truck starts moving forward. Since the speed is increasing, the ID input goes high. This causes the output of gate 32 to go high and puts the up/down counter in the count-up mode. The clutch comparison circuit compares members ① and ⑥ and when they are at the same speed causes the CK input to go high. This causes the counter to count up and its output becomes 010. This new count is decoded and a signal indicating clutch $\boxed{D}$ should be engaged is sent out. With the Q1 output of the counter low, the output of gate 49 is forced low and the output of gate 50 is the same as that of the output of the eight channel data selector. The data selector has as its selector input 101 which connects input X5 to the output. This is the line from the pressure switch connected to the clutch $\boxed{D}$ hydraulic line. When the hydraulic pressure builds up causing clutch $\boxed{D}$ to engage, the pressure switch closes and the counter counts up one more count. Low pass filters, consisting of the 100,000 ohm resistor and 0.01 microfarad capacitor on the inputs from the pressure switches, eliminate contact bounce. The Schmitt trigger on the output of the eight channel data selector increases the rise time of the clock signal to insure good clocking.

At this point the output of the counter is 010. The counter again receives its clock inputs from the CK input. With changes in vehicle speed, the up/down counter continues to count up and down as previously described.

Clutch Engagement Verification Circuit

This section of the system provides an additional safeguard to prevent the clutches from being engaged at the wrong time. This safeguard is in the form of a wide tolerance speed comparison. The circuitry to perform this comparison is shown in Figure 16. This fugure also shows the circuitry for the clutch member speed sensors. As previously stated, the sensors used are of the inductive type. One output of each of these sensors is connected to the ½V supply. The other output is run into a Schmitt trigger. The four Schmitt triggers are made from a quad comparator driving a CMOS invertor. This CMOS invertor decreases the output rise time. The combination of the 100,000 ohm resistor on the input and the 360,000 ohm feedback resistor allows operation with only 2.5 volts (5V peak to peak) out of the transducer when the supply voltage is 15 volts. The relationship between these resistors is:

$\frac{R_{feedback}}{7.5} = \frac{10^5 \text{ohm}}{2.5} \Rightarrow R_{feedback} = 300{,}000$ ohms. With a 5% tolerance on the resistors, this increases to 331,580 and therefore 360,000 ohms is used. The speed output for

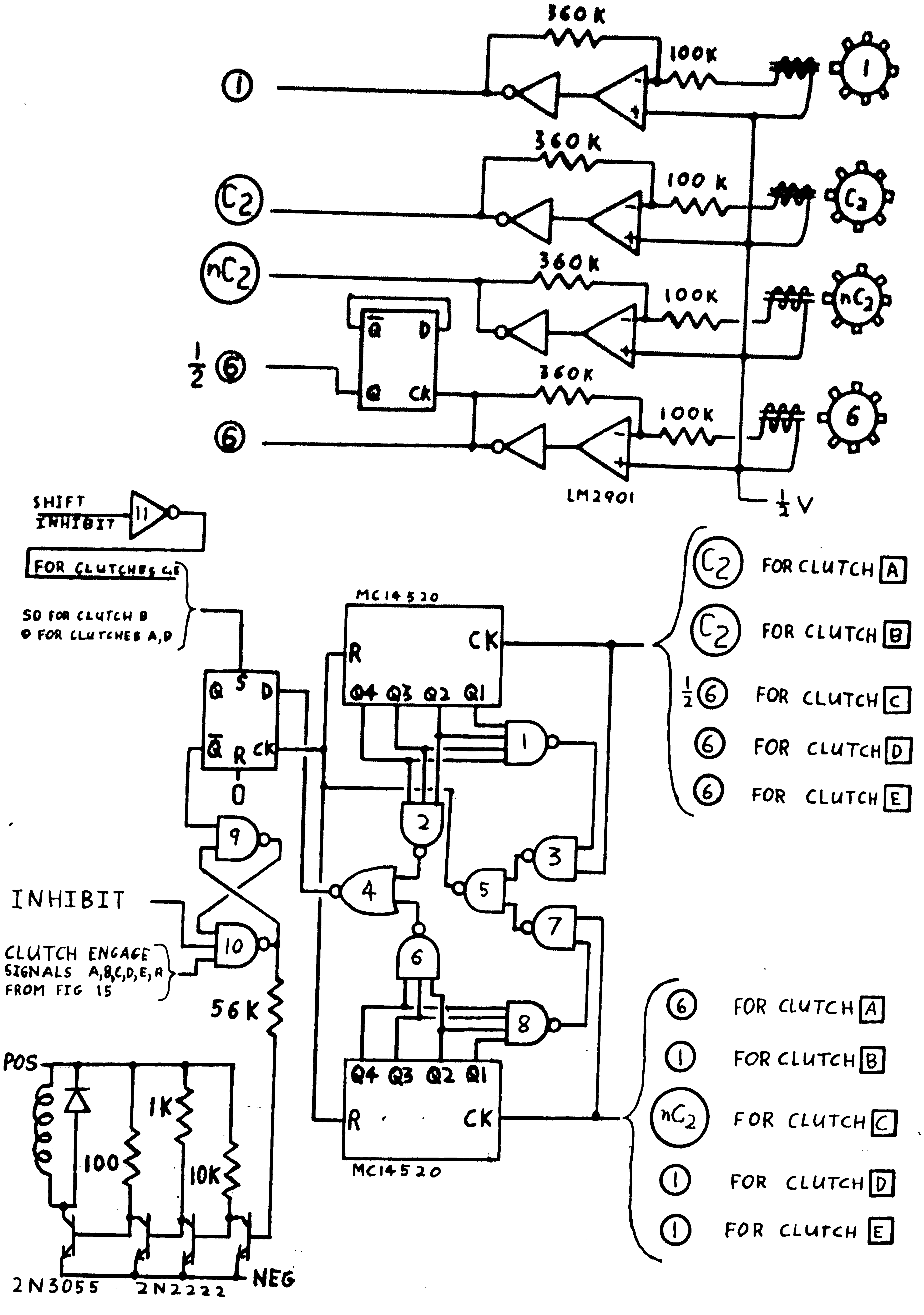

FIGURE 16 CLUTCH ENGAGEMENT VERIFICATION CIRCUIT

member ⑥ is run into a D flip-flop connected as a divide by two counter. This provides a ½ ⑥ output which is used for the engagement of clutch $\boxed{C}$.

The speed comparison circuit in Figure 16 is one of five identical circuits. The only difference in these circuits are in the inputs used. The inputs for clutches $\boxed{A}$ through $\boxed{E}$ are shown in Figure 16. The operation of this circuit is as follows. The speed signals for the two members of the particular clutch go into the clock inputs of the two counters. When one of the counters has counted to 16 the output of AND gate 1 or AND gate 8 goes high. The clock input will be low. When the clock input goes high the output of gate 3 or gate 7 will go low. This will cause the output of gate 5 to go high, and clock the D flip-flop. The delay of one half clock pulse is necessary to eliminate false clocking of the D flip-flop due to propagation delays in the counter. If both of the counters have counted to at least 15, the outputs of gates 2 and 6 will be low, causing the output of gate 4 to be high and driving the D input of the flip-flop high. This will in turn cause the $\overline{Q}$ output to go low when the flip-flop is clocked. This low input on gate 9 causes its output and therefore one of the inputs to gate 10 to go high. If the other two inputs to gate 10 also go high, the output of gate 10 will go low. This will turn on the solenoid valve. The driver for the solenoid valve is the same as that in

Figure 15 which was used for the alarm. Once the solenoid valve causes the clutch to engage and the shift takes place, the speed of the two members being compared will change. This will cause the output of the flip-flop to go high. However, since the output of gate 10 is low, one of the inputs to gate 9 will still be low and the clutch will remain engaged until the circuit in Figure 15 disengages it. Thus the clutch engagement verification circuit can keep a clutch from being engaged, but once the clutch is engaged, this circuit cannot cause it to be disengaged. When the transmission is put into the "start" range, clutch $\boxed{B}$ must be engaged whether or not the two halves are at the same speed. Therefore, when the SO output of the decoder in Figure 15 goes high, the set input on the flip-flop for clutch $\boxed{B}$ is forced high, causing the $\bar{Q}$ output to go low regardless of the D input. At zero speed the outputs from the inductive speed sensors will drop to zero and this circuit will not function. Therefore, to allow clutches $\boxed{C}$ and $\boxed{E}$ to be engaged when a shift is made into "drive" or "reverse", the shift inhibit signal is inverted and fed into the set input of the D flip-flop for these three clutches.

The circuit for clutch $\boxed{R}$ is not as complicated. Clutch $\boxed{R}$ is always engaged when the vehicle is at zero road speed with the engine at idle. The circuit for clutch $\boxed{R}$ contains only the solenoid valve driver and gates 9 and

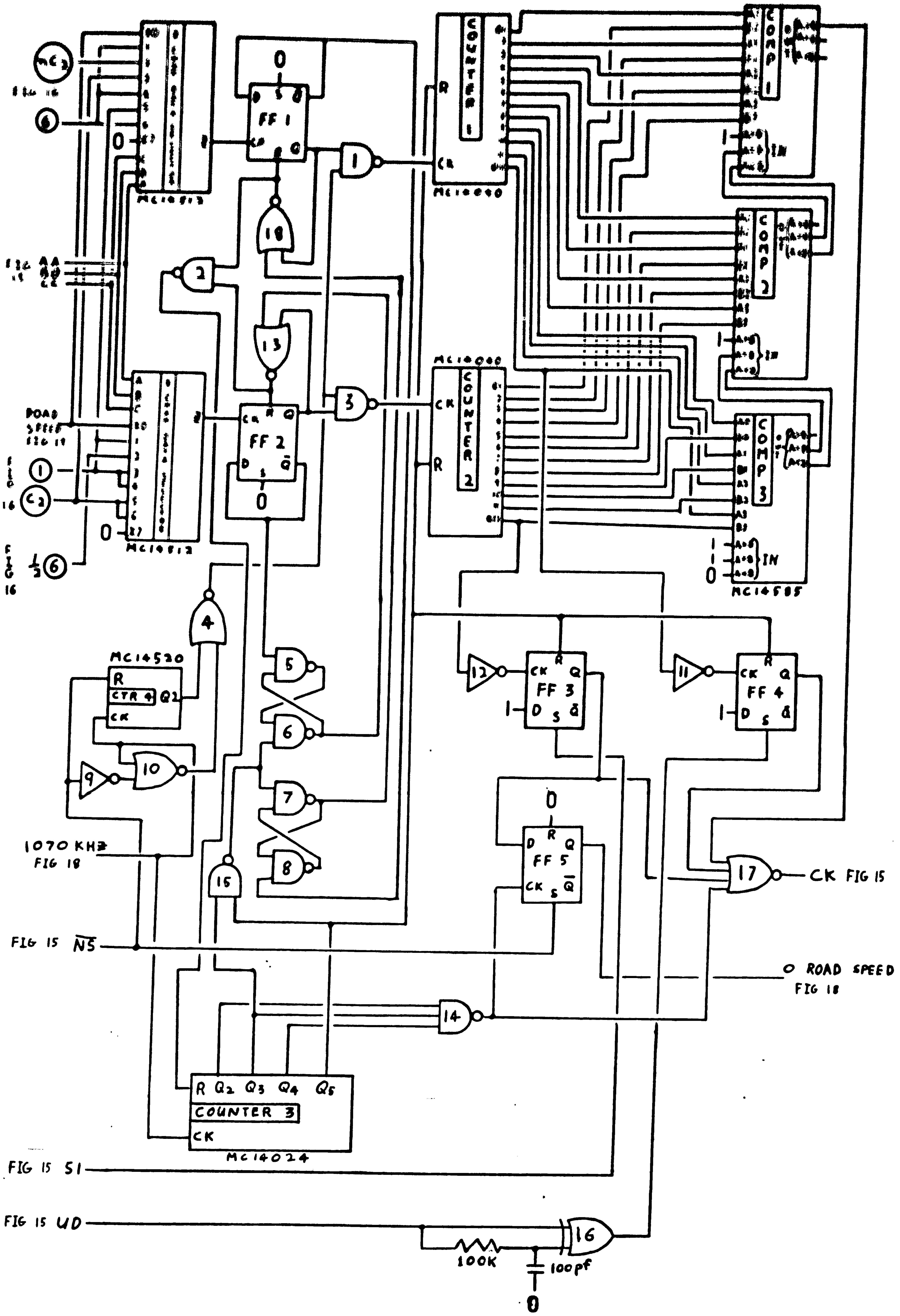

FIGURE 17 CLUTCH SPEED COMPARISON CIRCUIT

10. The input to gate 9 comes from the invertor from the SHIFT INHIBIT.

Clutch Speed Comparison Circuit

As previously stated, this circuit provides a clock pulse for the up/down counter in Figure 15 whenever the speeds of the two halves of the next clutch to be engaged are the same. As stated in Chapter 3, the periods of the signals from the two clutches are compared rather than the frequencies. With the transmission in "drive" or "reverse" the $\overline{NS}$ input will be high and counter 4 will be held reset. The 1070 KHZ input will be able to propagate through gates 10 and 4. This signal is used to clock counters 1 and 2. The two 8 channel data selectors determine the members whose speeds must be compared, based on the outputs of the up/down counter in Figure 15. The outputs from the data selectors are used to clock flip-flops 1 and 2 which are set up as divide by two counters. Only the operation of flip-flop 1 will be described since the operation of flip-flop 2 is the same. First, assume that the Q output of flip-flop 1 is low. When the clock input of flip-flop 1 goes from low to high, the Q output will go high and the $\overline{Q}$ output will go low. The high state of the Q output will allow the 1070 KHZ signal to clock counter 1. The low state of the $\overline{Q}$ output causes the flip-flop made up of gates 7 and 8 to go low. When the clock input to flip-flop 1 goes low and then high again, its outputs will change state and counter 1 will stop counting. This will make both inputs of gate 18 low and cause its output to go high. The high output of gate 18 will keep flip-flop 1 in its present state. Flip-flop 2 and the circuitry associated with it will go through a similar set of transitions. When the outputs of both gates 13 and 18 are high, the output of gate 2 will go low. This will allow counter 3 to start counting. When the Q2, Q3, and Q4 outputs of counter 3 go high, gate 14 will go low. This allows the output of gate 17 to go high if the count in counter 2 is greater than or equal to the count in counter 1. The pulse from the CK output will stay high approximately 2 microseconds. As counter 3 continues to count, Q 5 will go high. This will reset counters 1 and 2 and flip-flops 3 and 4. When Q3 goes high, with Q5 still high, the output of gate 15 will go low and set the two flip-flops made up of gates 5 and 6 and gate 7 and 8. With the outputs of gates 6 and 7 high, the outputs of gates 13 and 18 will go low and flip-flop 1 and flip-flop 2 will again be able to change state. Furthermore, the output of gate 2 will go high and counter 3 will be reset. This allows the period comparison cycle to begin all over again.

Flip-flops 3 and 4 are used to disable the CK output whenever counter 1 or counter 2 overflows. EXCLUSIVE-OR gate 16 in conjunction with the 100,000 ohm resistor and 100pf capacitor puts out a positive pulse every time the up/down input changes state. This pulse is used to set the Q output of flip-flop 4 high and disable the CK output. If this were not done, for part of the comparison cycle this circuit would compare the speeds for one clutch and for the rest of the comparison cycle it would compare it for another clutch. This will only happen, of course, if during the comparison cycle the up/down control changes and therefore, the next clutch to be engaged changes. The S1 input which goes to flip-flop 3 disables the CK output in a similar manner. From Table 2 it can be seen that when the transmission is in Range I and the speed is decreasing, the S1 output will be high. If a clock pulse is presented to the up/down counter at this time, the up/down counter will count down and the transmission will go into "neutral" or "start".

This circuitry is also used to determine zero road speed. When the transmission is in "neutral" or "start", the $\overline{NS}$ input will go low. This allows counter 4 to count and flip-flop 5 to change its state. Thus, the 1070 KHZ clock signal is divided by 4 and this lower frequency signal is substituted for the 1070 KHZ signal in the clutch speed comparison. With the transmission in this "neutral" or "start" range, the 8 channel data selectors will select road speed as the input. The circuitry will then proceed as it did previously to check the period of the signal from the road speed sensor. If this signal has a long enough period, counter 2 will overflow and the output of flip-flop 3 will go high. Thus, when the output of gate 14 goes high, the Q output of flip-flop 5 will go high indicating 0 road speed. The period of the road speed signal to cause overflow is 15 milliseconds. This corresponds to 1 mph.

Engine Speed Control

A general description of the operation of this control, as well as the operation of the road speed control, was given in Chapter 4. Figure 18 is a schematic diagram of the circuitry.

Engine speed is sensed by a Hall effect sensor. The output signal from this sensor is fed into a Schmitt trigger. The feedback resistor on this Schmitt trigger is 200,000 ohms since the output of the Hall sensor swings essentially between the two logic levels. The output from the Schmitt trigger runs into flip-flop 1 which, as explained in Chapter 3, divides its frequency by 2. This half engine speed signal is used to gate high frequency clock pulses into counters 4 and 5. The high frequency clock signals come from a crystal oscillator whose output frequency is divided in half by flip-flop 5. A description of the operation of this crystal oscillator can be found in Reference 13. When the Q output of flip-flop 1 has gone from high to low and back to high again, counters 4 and 5 will contain a count which is proportional to the

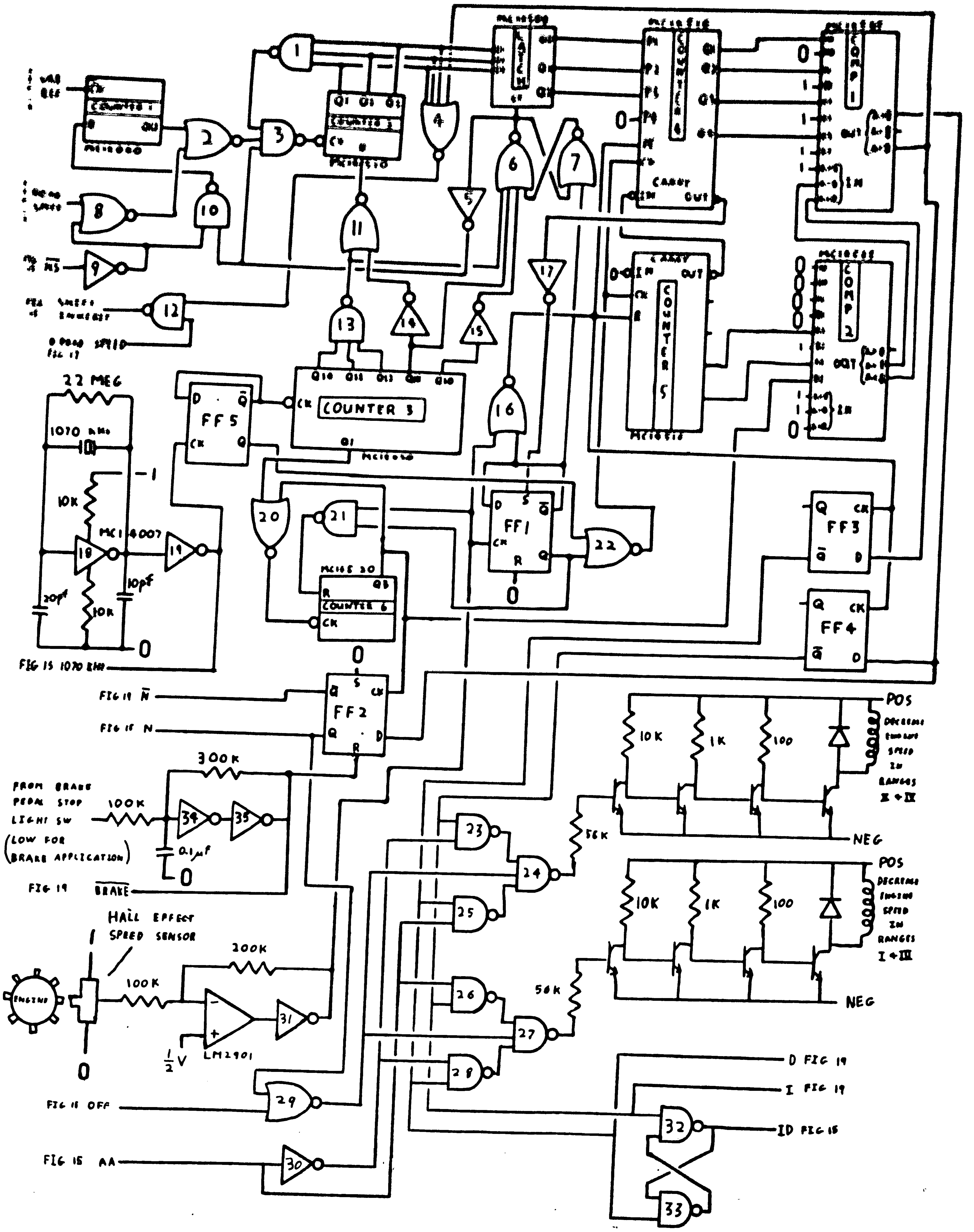

FIGURE 18 ENGINE SPEED CONTROLLER CIRCUIT

period of the signal from the engine speed sensor. This count is then compared to the reference by comparators 1 and 2. If the engine speed is below the set point, the A > B output of comparator 1 will go high. If the engine speed is greater than the set point, the A < B output will go high. The A0, B0, A1 and B1 inputs to comparator 2 are connected to the same logic level. This allows a variation of four counts in counters 4 and 5 without causing the output of comparator 1 to change. Thus, a deadband is established. The relationship of this deadband and of the set point will be discussed later.

Flip-flops 3 and 4 are used to store the outputs of comparator 1 while a new count and comparison cycle is in progress. Gates 23 through 28 are used to gate the signals from flip-flops 3 and 4 to the solenoid valve drivers. As stated in Chapter 3, it is necessary to reverse the direction of the hydraulic pump/motor control each time a new range is entered. In ranges I and III, input AA, from Figure 15, is low. This gates the increase loading (decrease engine speed) signal from flip-flop 3 into the lower solenoid valve driver. The $\overline{Q}$ outputs of flip-flops 3 and 4 are used because the solenoid valve driver must have a low logic level to turn on the solenoid valve. Whenever it is determined that a shift should be made, and therefore a new clutch engaged, the ratio of the transmission should be held constant. As seen from Table 2, a shift occurs whenever the Q1 output of the up/down counter in Figure 15 is low. However, when the transmission is in "reverse", the transmission ratio must be allowed to change. The off input from Figure 15 is high whenever these conditions are met. This signal causes the outputs of gates 24 and 27 to go high.

Whenever the CARRY OUT output of counter 4 goes low, indicating that the next clock pulse will cause an overflow condition, the Q output of flip-flop 1 is forced high, thereby inhibiting further clock pulses. The output from gate 16 presets counter 4 and resets counter 5 when the signal from the engine speed sensor goes low following a count-comparison cycle.

The signal which is preset into counter 4, and allows engine speed to drop to "idle" as road speed drops to zero, is stored in the latch. The input to the latch comes from counter 2 which counts road speed pulses to give an output proportional to road speed. The time base for this frequency counter is the crystal oscillator. The output of the crystal oscillator is divided down by counter 3. The outputs of counter 3 are decoded to give strobe and reset pulses. With the input to gate 7 high, the strobe signal will go high when the Q10, Q12, Q13 and Q14 outputs of counter 3 are high and when the Q11 output is low. If the input to gate 7 goes low while the strobe signal is high, then the strobe signal will remain high. However, if the input to gate 7 goes low before the strobe signal goes high, the strobe signal will be held low until the input to gate 7 goes high. The input to gate 7 goes high whenever counters 4 and 5 are counting. Thus, the strobe signal is prevented from going high while the preset enable input is high. The strobe pulse width is 1 millisecond while the period of the engine speed signal will never be greater than ½ millisecond. Therefore, the strobe pulse will always appear, but my be of shorter duration. When the strobe pulse goes high, the output of gate 3 is forced high preventing further clocking of the counter. The reset pulse to counter 2 will be high when the Q11, Q12, Q13 and Q14 outputs of counter 3 are high. The decoding of the outputs of counter 3 to provide the strobe and reset pulses is insensitive to the propogation delays between the stages of the counter.

If the input frequency to counter 2 is high enough that this counter counts to 7, gate 1 will go low and stop any further counting until the counter is reset. Thus, an increase in the road speed signal above 250 Hz will give no further increase in engine speed. This corresponds to 200 revolutions per minute of the output shaft of the transmission with 75 pulses per revolution.

When the transmission is in "neutral" or "start", the $\overline{NS}$ input will be low. This forces the output of gate 8 low and allows counter 1 to divide the variable reference from Figure 19 by 2^{12}. This gives an input to the frequency counter which varies between 293 Hz and 29.3 Hz. The increase and decrease signals (I,D) will then be sent to Figure 19 where they will control the engine fuel injection pump rack position. The two solenoid valve drivers in this circuit will be held off by the OFF input. The strobe pulse is used to reset counter 1. Thus, counter 1 starts out counting from 0 at the beginning of each frequency measurement period for counter 2. This prevents a high to low transition of the output of counter 1 when the input to counter 1 has a period less than 30 milliseconds.

The SHIFT INHIBIT output is low whenever the vehicle is not moving and the engine speed is "idle". When the transmission is in "drive" or "reverse", the fact that the engine speed is "idle" indicates that the road speed is zero. Thus, the 0 ROAD SPEED input only goes low when the road speed is not zero and the transmission is in "neutral" or "start". The engine speed is at "idle" when the output of counter 2 is zero and the A > B output of comparator 1 is zero. This indicates that the engine speed is not being further decreased and therefore is the idle value called for by counter 2. Gate 4 is used to sense this condition.

The limits for the deadband of the engine speed controller are 236 counts and 219 counts. This gives a 4 count deadband and allows control of engine speed within 0.89% of the center of the deadband. With counter 4 preset to 0000, a count of 237 corresponds to an engine speed of 900 rpm. With counter preset to 0111, only 125 clock pulses are necessary to bring the counter output up to 237. This corresponds to an engine speed of 1700 rpm. These calculations were made assuming an output from the engine speed sensor of 150 pulses per revolution of the engine output shaft.

The remainder of the circuitry in Figure 18 will be described in the road speed section, which will be discussed next.

Road Speed Control

The road speed control circuitry is shown in Figure 19. Note: Figure 19 appears on two pages. A general description of the operation of the road speed governor and its interaction with the engine speed governor has already been given and therefore will not be repeated in this section.

The road speed input comes from a Hall effect sensor and is run into a Schmitt trigger just as in the case of the engine speed sensor. The frequency of this signal is divided in half by flip-flop 1. The signal from flip-flop 1 is then used to gate clock pulses from a variable reference into counters 2, 3 and 4. When the transmission is in "drive high", the HI input is high. This allows counter 1 to divide the road speed signal by 10. When the transmission is in "drive low" or "reverse", the HI input is

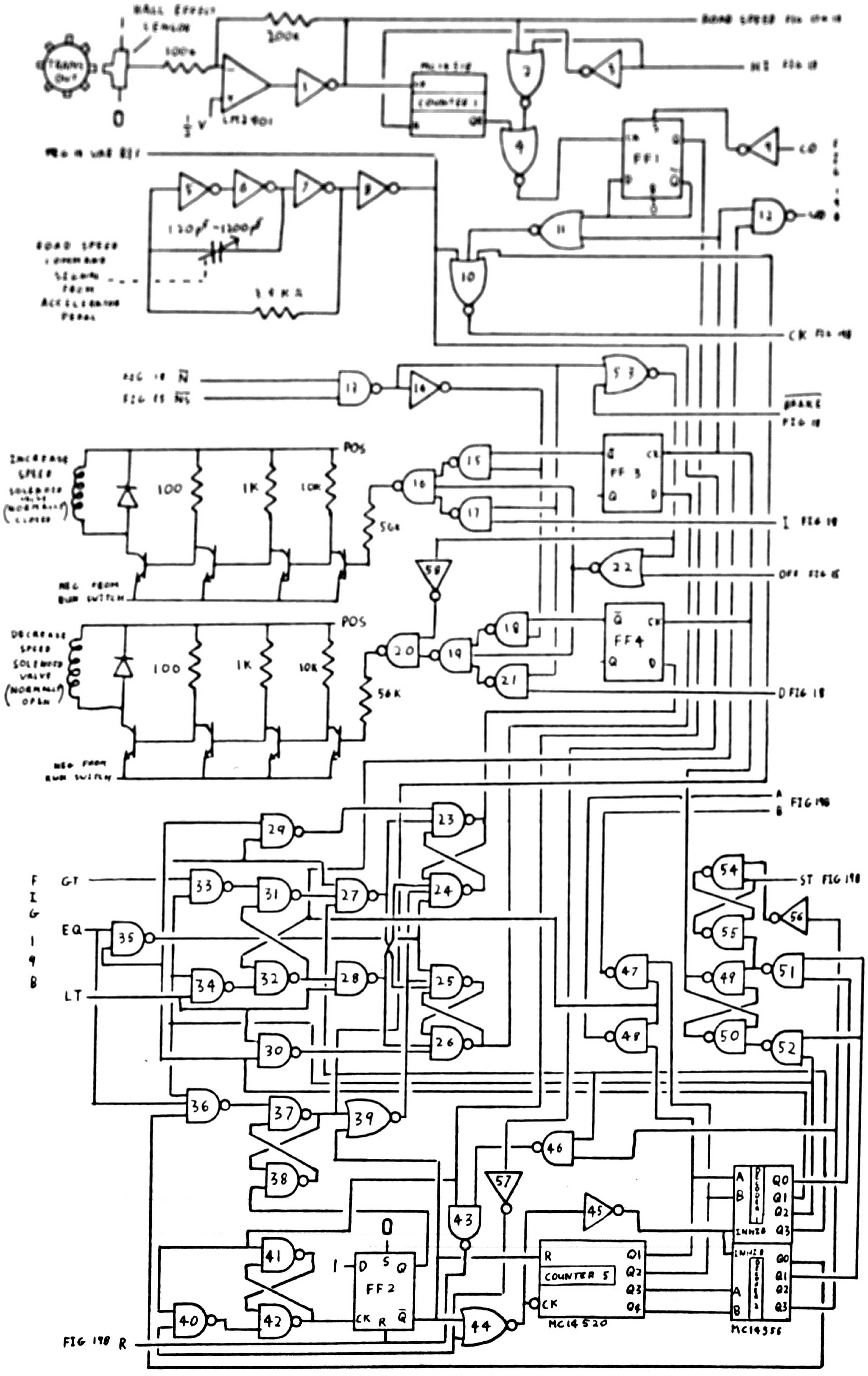

FIGURE 19A ROAD SPEED CONTROLLER CIRCUIT

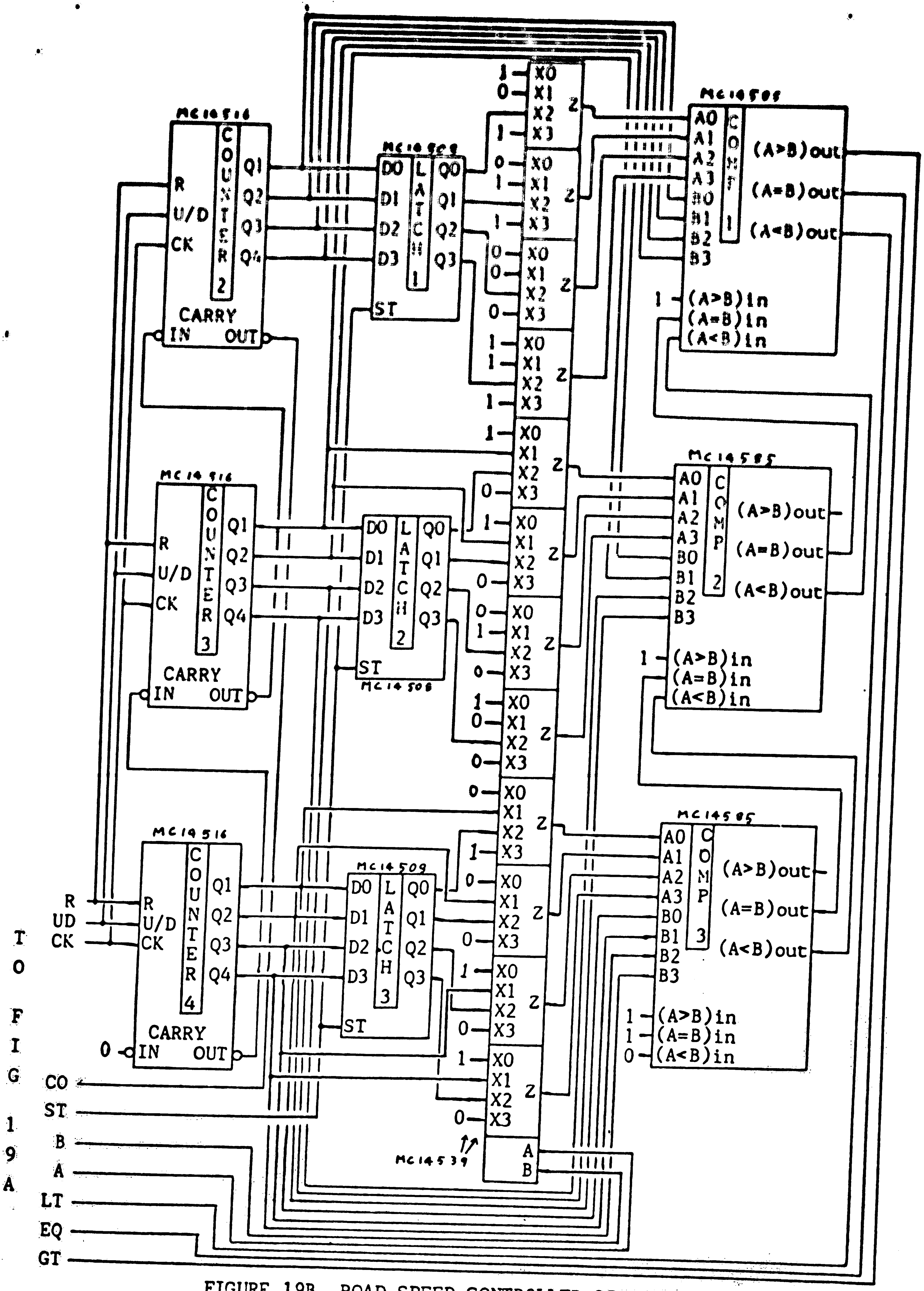

FIGURE 19B ROAD SPEED CONTROLLER CIRCUIT low and the road speed signal goes to flip-flop 1 without being divided in frequency. The variable reference is constructed from 4 CMOS inverters. The 120 pf to 1,200 pf variable capacitor varies the frequency of this oscillator. The accelerator pedal is mechanically linked to this capacitor. Depressing the accelerator pedal causes the capacitance to decrease and the frequency to increase. A further description of this oscillator can be found in Reference 14.

Once a series of clock pulses have been gated into counters 2, 3 and 4 by a low to high to low transition of the $\overline{Q}$ output of flip-flop 1, a series of comparisons are made between the outputs of these counters and the set points. When the Q output of flip-flop 1 goes high and the output of the variable reference goes low, the output of gate 40 will go low. This causes the output of the flip-flop consisting of gates 41 and 42 to go high. Further transitions of the output of the variable reference have no effect on the output of this flip-flop. The high output on the gate 42 clocks the D flip-flop and causes the Q output to go high and the $\overline{Q}$ output to go low. Thus, counter 5 is allowed to count. The first clock pulse to counter 5 will occur ½ cycle later when the output of the variable reference goes high. Thus a minimum delay of ½ cycle of the variable reference is obtained before the Q1 output of the decoder goes high. The INHIBIT inputs on the decoders are used to keep the decoded outputs low for ½ clock cycle after counter 5 is clocked. This eliminates incorrect outputs due to propagation delays in counter 5.

When the output of counter 5 is one (0001), the Q1 output of decoder 1 and the Q0 output of decoder 2 will be high. Also the A input to the MC14539 data selectors will be low and the B input will be high. This selects the outputs of the latches to be compared with the outputs of the counters. The latches contain the previously computed intermediate set point for the road speed. If the road speed is equal to the previously computed value, the A = B output will go high. If the road speed is greater than the previously computed value, the A> B output will go high and if the road speed is less than the previously computed value, the A< B output will go high. If the A = B output goes high, the outputs of the flip-flops made up of gates 23 and 24 and gates 25 and 26 will go low. If the A> B output is high, the flip-flop made up of gates 23 and 24 will go high. If the A< B output is high, the output of the flip-flop made up of gates 25 and 26 will go high. The next count of counter 5 causes the Q2 output of decoder 1 to go high. Also, the A input to the data selectors will go high and the B input will go low. Thus the road speed value stored in the counters is compared to the deadband limits. A deadband is established in the same way as it was in the engine speed controller. If the road speed is within the deadband, the output of gate 36 will go low forcing the output of the flip-flop made up of gates 37 and 38 high. This forces the output of gate 39 and therefore gates 23 and 26 low. If the road speed is outside of the deadband, then the output of either gate 31 or 32 will go high depending upon whether the road speed is higher or lower than the deadband. The next count of counter 5 causes the Q3 output of decoder 1 to go high. The A and B inputs to the data selector will both be either high or low. This selects either the upper or lower approach band limits for comparison to the counter outputs. If in the previous comparison the road speed was below the deadband, the output of gate 31 will be low and the A and B inputs will be high. If the road speed was greater than the deadband, the A and B inputs will be low. If the road speed is above the deadband and outside the approach band, the output of gate 27 will go low. This will force the output of the decrease flip-flop (gates 23 and 24) high and the output of increase flip-flop (gates 25 and 26) low. If the road speed is within the deadband, the increase and decrease flip-flops will retain their present states. The operation of the circuitry when the road speed is below the deadband is similar.

The next count of counter 5 causes the Q0 output of decoder 1 and Q1 output of decoder 2 to go high. This forces the output of gate 51 low, which sets the outputs of the two flip-flops made from gates 49 and 50 and gates 54 and 55 high. The high transitions of gate 49 clocks flip-flops 3 and 4 which pick up the increase and decrease information from the increase and decrease flip-flops. Flip-flops 3 and 4 store this information until the next comparison cycle when new increase and decrease commands are given. The high output of gate 49 forces the output of gate 11 low. If the output of gate 37 is low (the road speed is not within the deadband) then the clock pulses from the variable reference will cause the counter to count. If the output of gate 31 is high (indicating road speed above the deadband), the UD inputs to the up/down counters will be low and they will count down. If the road speed is above the deadband, the counters will count up. After the proper number of counts has been made by the up/down counters (this number must be determined experimentally; the circuitry shows it as two) the output of gate 52 will go low and clocking of the up/down counters will cease. This will also force the output of gate 12 high so that the up/down counters will count up when counting road speed. The strobe pulse will go low when the Q3 output of decoder 2 goes high. Thus, the next value of the intermediate set point will be stored in the latch.

When the Q3 outputs of both decoders are high, the output of gate 46 will go low. This will force the output of gate 43 high and reset flip-flop 2 and the up/down counters. This in turn will reset counter 5, the flip-flop made up of gates 37 and 38, and the increase and decrease flip-flops. When another road speed counting sequence is initiated by flip-flop 1, the low state of the Q output will force the output of gate 42 low and reset the flip-flop made up of gates 41 and 42. Thus, all of the flip-flops and counters will be ready for another series of comparisons between the up/down counter outputs and the set points.

The drivers for the solenoid valves are the same as in other parts of the system. The decrease solenoid valve is normally open. Therefore the signal from gate 19 is inverted by gate 20. The OFF input functions the same as in Figure 18.

When the transmission is in "neutral" or "start", the $\overline{NS}$ input goes low. This switches control of the engine throttle to the engine controller.

The limits of the deadband are 2624 counts and 2687 counts. This gives a deadband 64 counts wide, which puts the edges of the deadband 1.2% away from the center. The lower approach band is 2819 counts. This is a higher number of counts than the deadband since period is measured rather than frequency. The upper approach band is 2492 counts. There are 133 counts between the edges of the deadband and the limits of the approach bands. This corresponds to 5% wide deadbands. These calculations were made based on 75 pulses from the road speed sensor for every revolution of the output shaft of the transmission. The values for the deadband and approach bands may have to be modified based on actual tests with the control system installed in a vehicle.

When the driver makes a brake application, the input from the brake light switch goes low (for positive ground vehicles). The input from the brake light switch goes into a Schmitt trigger made from gates 34 and 35 in Figure 18. A 300,000 ohm feedback resistor is used due to the variations in the threshold of the CMOS inverter. The 100,000 ohm resistor limits the input current to gate 34 to less than 10 ma in the presence of transients and prevents the gate from being damaged. The 0.1 microfarad capacitor slows down the Schmitt trigger and reduces its sensitivity to contact bounce. The low output of the Schmitt trigger allows flip-flop 2 to change state. This output also goes to Figure 19 where it causes both solenoid valves to turn off. Thus, applying the brakes causes the engine fuel injection pump rack to be moved to the minimum fuel position.

As the vehicle slows down, a point is reached where the road speed is too low to maintain the engine speed.

This is sensed by comparing the output of counters 4 and 5 in Figure 18 to a set point which is 5 counts higher than the count corresponding to the lower edge of the deadband. This corresponds to an engine speed which is 2% low. Thus, rather than the single comparison between the outputs of counters 4 and 5, described previously, two comparisons are made. When the Q output of flip-flop 1 goes high following the low to high transition of the CK input, the outputof gate 21 goes low. This allows counter 6 to start counting. When the counter begins counting the Q3 output is low and therefore the B3 input to comparitor 2 is low. Thus the comparison for engine speed 2% low is made. If the engine speed is low, the A > B output will go high. When the Q3 output of counter 6 goes high, the signal from the A > B output will be clocked into flip-flop 2 and held until the Q3 output makes another low to high transistion. The N output connected to the Q output of flip-flop 2 is used to disengage all the clutches in the transmission. It also turns off the two solenoid valves controlling hydraulic pump/motor displacement. The $\overline{N}$ output switches control of the fuel injection pump rack to the engine speed controller. It also forces the output of gate 53 in Figure 19 low allowing the solenoid valves to be turned on. The high state of the Q3 output of counter 6 forces the output of gate 21 low. This stops further counting of counter 6. The high signal applied to the B3 input of comparator 2 allows the comparison between road speed and the deadband to be made. When the CK input of flip-flop 1 goes low again the output of gate 16 goes high and clocks flip-flop 3 and 4. The sequences previously described are then repeated.

CHAPTER 9 THE PROTOTYPE

The details of this system design were based on a paper mechanical design of the transmission. The working prototype unit could be somewhat changed from the original design insofar as the number of stages of reduction, gear ratios, etc. are concerned. A modification of the final electronic system details then would be required. If it is elected to equip a prototype transmission with the proposed system and install the unit in a vehicle, final details such as approach band widths and dead band width can be established experimentally.

By combining the sophisticated solid state control system proposed, with the advanced MAPT concept, maximum driver convenience can be combined with optimum vehicle performance. In addition, built-in safeguards protect the equipment against the possibility of damage thru driver abuse.

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