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VEHICLE SAFETY TELEMETRY FOR AUTOMATED HIGHWAYS

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16. Abstract The concept of automated highways providing the means for motor vehicles to travel between interurban centers without active driver participation has been forwarded by many investigators. Breakdowns of the vehicles using such a highway could be hazardous to life or, at the least, interrupt traffic flow. The proper operation of a vehicle approaching an automated highway would have to be assessed to a high degree of certainty before that vehicle could be allowed entry.

This report summarizes the results of a study of several areas germane to the automated highway and vehicle system. The current state-of-the-art of automatic vehicle testing and diagnosis was investigated and it was determined that the emphasis is primarily centered on the proper operation of the engine. Lateral and longitudinal guidance technologies, including speed control and headway sensing for collision avoidance, were reviewed. The principal guidance technique remains the buried wire. Speed control and headway sensing, even though they show the same basic elements in the braking and fuel systems, are proceeding independently. The applications of on-board electronic and microprocessor techniques were investigated and here again each application (emission control, spark advance, or anti-slip braking) is being treated as an independent problem. The final portion of the report presents various processor systems leading to a proposed unified bus system of distributed processors for accomplishing the various functions and testing required for vehicles equipped to use automated highways.

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FOREWORD

The concept of interurban, 100- to 400-mile, automated highways has been studied by several investigators. The highway systems forecasted, as a result of these studies, would have some or all lanes equipped for lateral guidance and longitudinal speed control. Any breakdown, whether sudden or gradual, would cause a flow blockage and could be extremely hazardous to vehicles which are following or in adjacent lanes. Therefore, so that the operations, safety, and traffic flow are maintained, the entry of improperly performing, incompletely equipped, or potentially unreliable vehicles should be discouraged or prevented.

The judgment as to the proper operation criteria being met by the vehicle obviously cannot be left to the driver: (1) because of the driver's inability to determine if the automatic equipment is performing adequately, while the vehicle is under manual control; (2) because of driver acquired tolerance for marginal performance; and (3) because of driver impatience about the possibility of a delay. An automatic test and checkout procedure is, therefore, called for prior to the entry of the vehicle onto the automated highway. These tests may require manual intervention in a test facility, be performed semi-automatically, or be accomplished "on the fly" without driver involvement.

Several areas of technology relating to vehicles and automated highways were investigated and the results are presented in this report. It was determined which vehicular sensors are in current use and which are forecast for future use. The applications of these sensors for both on vehicle equipments and in several off-vehicle test and diagnosis systems were also investigated. The operations and test philosophies of current test-systems are presented, as well as the possible incorporation of these systems or sensors into on-board checkout systems.

Lateral and longitudinal guidance methodologies, as well as speed control and headway sensing techniques were reviewed. It appears that the sensors for automotive lateral guidance are not common to any other vehicular sensor systems while longitudinal guidance, speed, and headway controls share similar basic elements in the engine fuel supplying and braking areas. These technologies were reviewed to estimate the sort of criteria that should be established in allowing or denying entry of vehicles to an automated highway. The criteria for rejecting vehicles on the basis that all subsystems are not working correctly can be established by wayside or on-board checkout or diagnostic systems. Denial of entry to a vehicle, based on the estimate that it probably cannot complete the journey, requires an assessment of the remaining operating life in all critical operating subsystems or elements. This requires that historical replacement data and degree of usage be provided, as well as the subsystems operational checks being performed before an estimate can be made that a particular vehicle is likely to fail. The sensed indications alone, without the parts life data, appears insufficient to establish that entry is warranted.

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CONTENTS

Figures

Tables

SECTION I

DIAGNOSTIC TECHNOLOGIES

A. INTRODUCTION

Current work with vehicle diagnostic and testing equipment is almost totally concerned with only the spark or compression ignition engines. The remainder of the vehicle is not a concern at the present. The approach to diagnosis is to measure performance parameters with testing devices and to see if specifications are being met. If an improper indication is obtained, then adjustments or repairs are dictated; sometimes by the test equipment itself. The test instruments rely on several different types of sensors and transducers in measuring the engine performance parameters.

The first part of this section discusses the various sensors required for automotive performance measurements for both diagnostic equipment and other automotive subsystems. Later parts of the section discuss the aggregation of these sensors into indicating systems. The final parts of this section discuss several state-of-the-art automotive and truck, or bus engine, diagnostic systems; as well as the sensors used and the testing methodologies.

B. SENSORS AND SYSTEMS

The repairing of automobiles relies greatly on the diagnostic skill of the mechanic. Automobile manufacturers and automotive testing equipment developers have attempted to aid this skill and develop it in several ways. A host of publications ranging from shop manuals individual vehicles, factory service bulletins, monthly periodicals, and columns in magazines and newspapers are a continuing source of educational information for the mechanic and other service personnel and operators.

Another approach to improving the repair art has been the development of specialized automotive test equipment. This equipment has been geared to testing some particular aspect of the vehicle. Usually the equipment is designed to measure a function or subsystem such as ignition system performance, front end alignment, or engine power output and can be used to assess this same functioning unit on many different types of vehicles.

The development of the test equipment and educational diagnostic aids have generally kept pace with changes in the auto industry with regard to the basic internal combustion engine. The proliferation of accessories on vehicles together with mandated emissions and economy standards have had an impact on the auto service industry not unlike the introduction of color TV on radio and television repair organizations. This impact has caused the diagnosing of motor vehicle faults to become, mainly, a very logical structured process. There are still those idiosyncracies of certain models or makes which can only be discovered by talented individuals, but in general the proper following of a path through a diagnosis "tree" structure will lead to the malfunction (Ref. 1). These diagnostic trees are a series of tests, which lead to certain indications of either improper or faulty operation, dictated primarily by a complaint or improper function. The path through the tree is therefore determined, through the logical elimination of possible contributors to the faulty action, leading to the actual cause of the problem. The successful use of these diagnostic trees relies on making all of the tests called for and noting the results. Playing hunches or skipping steps has no place in the use of these aids.

So that the tests can be properly made, the test equipment manufacturers have developed many types of instruments and sensors. They have also combined and assembled these instruments into unified test consoles, usually mobile, to facilitate using the equipment near the vehicle. These unified test equipments are available from several manufacturers. The types of functions they are designed to measure are:

(1) Ignition timing.

(2) Primary coil voltage.

(3) Voltage waveshape of primary coil.

(4) Secondary coil voltage.

(5) Voltage waveshape of secondary coil.

(6) Ignition point dwell angle.

(7) Ingition point resistance (closed).

(8) Alternator output voltage.

(9) Alternator field current (voltage).

(10) Battery voltage - cranking.

(11) Battery voltage - charging.

(12) Starter voltage.

(13) Starter current.

(14) Fuel pump pressure.

(15) Engine speed.

(16) Intake manifold depression (vacuum)

(17) Air-fuel mixture

(18) Exhaust CO (carbon monoxide)

(19) Exhaust HC (hydrocarbons)

The functions listed are those necessary to ascertain the causes of the vast majority of common complaints concerning the ignition, charging, engine electrical, and engine fuel systems.

1. Sensors

a. Automotive Sensors. The use of sensors on automotive vehicles, until recently, was to merely operate instruments or to provide other indications of vehicle performance or condition to the operator. Speedometer, fuel level and temperature gauges were all that were usually provided, together with "no-charge" and low oil pressure warning lights, and a high beam indicator. The incorporation of more and more accessories, emission controls, safety equipment, and diagnostic test points have resulted in a substantial increase in the on-board sensor complement. The requirement for additional sensors for safety and automatic equipment will undoubtedly increase, particularly with the increasing use of microelectronics.

The parameters measured in the past included pressure (oil), temperature (coolant), current (battery), voltage (charging regulator), fluid level (gasoline), rotational velocity (speedometer), linear motion (brake light switch), and other switch position indicators. With the exception of a few special purpose parameter measurements, the mentioned parameters are still of principal importance, but in much greater number.

b. Level Sensors. Remote indicating level sensors have found application primarily in military vehicles, but there has been some application in civilian vehicles. The level sensor avoids the use of dipsticks and allows fluid reservoirs to be placed without consideration for visual inspection. Level sensors in current use are:

(1) Coolant (Radiator)

(2) Coolant (Reservoir)

(3) Transmission Fluid

(4) Brake Master Cylinder(s)

(5) Brake Fluid Reservoir

(6) Power Steering Fluid

(7) Lubricating Oil

(8) Fuel Level

(9) Windshield Washer Fluid

(10) Differential Lube

(11) Battery Electrolyte

The battery electrolyte level sensor may be thought of as a switch contact or voltage probe because it is a metallic conductor which pierces the wall of the battery. The metal contact on the inside wall is positioned at the low limit of electrolyte. When the electrolyte level is above or "wetting" the contact, the contact senses the electrical potential of the electrolyte. When the electrolyte level drops below the low limit, due to water loss for example, the contact is open circuited and no voltage is sensed. This technique has been employed on the Volkswagen and Toyota vehicles.

The most familiar level sensor which provides an analog output is the fuel sensor. This is generally a rheostat gauge where the moveable arm of the rheostat is operated by a float which rests on the surface of the fuel. The varying resistance of the rheostat, as fuel level changes, controls a current to a remote fuel gauge. Other level sensors proposed for this function and developed for aircraft or other uses include float operated switches and acoustic or capacitance operated level sensors.

A fuel capacitance sensor is currently under development by General Motors (Ref. 2). The sensing element consists of two coaxial cylindrical tubes immersed vertically into the fuel. The dielectric constant of gasoline is about twice that of air and the change in capacity (empty to full) is purported to be about two to one (60 to 130 pf). This capacity is compared in a circuit with a standard capacitor. The circuit develops a pulse train with the duration (width) of the pulses proportional to the capacitance or the fuel level sensed.

Acoustic sensors have not received attention for automobile application. The principle relies on the excellent reflectivity of the fuel/air interface to an acoustic pulse. The time delay of an acoustic pulse, from transmission to return, determines either the height of the fluid or the distance to the fluid depending on where the transducer is placed. The time delay and the speed of sound (in fuel or air) yields the physical distance and therefore the fluid level. This technique is usually reserved for hazardous or corrosive fluids.

The float operated switch is in current use in automotive application and in one form consists of a non-ferrous L-shaped tube which contains a magnetic reed switch (see Figure 1). The tube is closed on one end but the other is open to allow egress for the switch wires. A cylindrical, plastic float with an axial hole rides on the L-shaped tube. The float contains a magnet so that when it reaches a certain position on the tube the reed switch is actuated. The tube may be placed with the "L" in the normal position or in the inverted position and thereby it indicates when the sensed level is either below or above the desired position.

In deep tank applications, the float switch is installed on a long tube containing several switches. Several discrete levels can then be sensed.

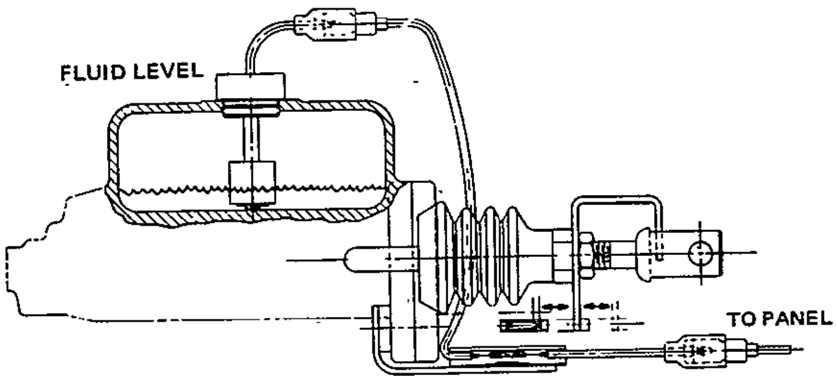

Figure 1. Fluid Level Switch

c. Rotational Motion Sensors. The speedometer has been the only universally used rotational motion sensor and indicator on motor vehicles. In most applications, the speedometer contains both the rotary motion sensor and indicator in the panel instrument; the speedometer cable merely being a means to translate the rotary motion of the drive line to the instrument panel. The actual sensor is a rotating magnet driven by the cable and sensed by a drag cup. The cup is of thin aluminum which has eddy currents induced in it by the rotating magnetic field. The drag force on the cup is balanced against the restoring torque of a spring yielding a rotary displacement proportional to the speed of the rotating magnet.

Transducers for tachometers (Refs. 3 and 4) developing analog signals proportional to rotary speed have been dc generators, but, more recently, pulse-integrating circuits have taken over the function. The primary reason for using electronics in place of dc generators has been cost. The widespread use of engine speed tachometers, driven from the primary side of the ignition system, has made the development of an integrated circuit (IC) solely for the function economically viable. At least two semiconductor manufacturers are making such a semiconductor IC.

Tachometers using a pulse source other than an electrical contact (as in the ignition) have been developed and are in widespread industrial use. The sensor often used is a biased magnetic pickup (Ref. 5) similar to a tape head or a variable reluctance device that senses the presence of ferrous material in the magnetic path. These devices sense promontories or notches on the rotating device, such as the starter ring gear teeth on the flywheel or the machined top-dead-center (TDC) notch on the vibration damper.

Sensing of the TDC mark for engine ignition timing is now being facilitated by the auto manufacturers' inclusion of a bracket for the mounting of a magnetic sensor. This sensor is supplied by the test mounting of a magnetic sensor. This sensor is supplied by the test equipment manufacturer and, when installed, permits direct reading of engine advance or retard on the test meter.

In a similar manner a flywheel ring gear sensor is being used by engine diagnostic devices for power-contribution tests. The many teeth on this gear allow the changes in angular accelerations to be determined, to fair precision, during a revolution. The relative forces contributed by the different cylinders during engine revolutions can then be determined.

Two of the magnetic pickups - one at each end of the driveline - allow not only rotation but angular displacement, as a result of torque to be measured. This technique is currently being developed for marine and industrial engines to provide a continual measure of horsepower output.

Other rotational speeds being measured for automatic diagnosis are primarily in the heater/air-conditioning system. These are fan-motor velocities which are measured together with the current and voltage to determine proper operation.

Electric engine coolant fan speed as well as power-steering pump and air-conditioner compressor speed are future candidates for velocity measurements. The latter two could provide a rapid indication of a broken drive belt.

In the area of a anti-skid brake system for trucks (Ref. 6) considerable work has been done to develop sensors which measure wheel velocity (relative to a fixed point on the vehicle) as part of a system to prevent wheel lock-up when brakes are applied....especially in panic situations. In conjunction with this, some rather sophisticated proximity and velocity sensors have been developed which might have application in other areas of safety measurement....such as steering or suspension checkout.

d. <u>Switch Sensors</u>. Mechanical switches are now being used for the operation of safety-related indicators. The same type of door switches, which operate the dome light, is also used to operate a "door unlocked" indicator by sensing the push-button control position. This same switch type is also used to monitor a partially open door, hood, or trunk condition for safety or anti-theft purposes.

The OK Panel used on the Toyota and discussed in another part of this section utilizes continuity wires molded into the brake lining to indicate when wear has reached a certain point. The grounding contact between the wire in the lining and the rotor or drum on brake application operates as a mechanical switch. The wear limit may be indicated by contact being made on each brake application, as above, or by an open circuit when the wire wears through as the wear limit is reached. This latter method does not rely on a contact and can also indicate if the sensor wire is open-circuited.

A linear-motion switch, (which has generally supplanted a pressure switch) is the stop-light switch. This switch is operated by the initial movement of the brake pedal and is tolerant of a great deal of over-travel which would occur in the case of low pedal. A switch to detect low pedal (Refs. 7 and 8) has been employed on military vehicles. This switch is mechanized by a stationary reed-switch mounted near the brake master-cylinder linkage. A small magnet on the linkage is positioned to operate the reed switch when pedal travel reaches a prescribed limit.

e. Special Sensors. Sensors for special applications or parameter measures are in some production vehicles and in research use. One of the newest, brought about by the triple catalytic converter, is the lambda sensor (Ref. 9) or oxygen-sensor. This is a zirconium-dioxide electrolyte sensor, which responds to the partial pressure of oxygen in the exhaust stream. This partial pressure changes by factors of about 10^7 to 10^{19} when the mixture changes from slightly rich to slightly lean. The sensor output, which is typically 800 millivolts or more on the rich side and less than 100 millivolts on the lean, is used in a closed-loop fuel injection system to maintain a constant air/fuel ratio.

The Zirconia Exhaust-Oxygen Gas Sensor consists of a zirconia ceramic tube with porous platinum electrodes on both its inner and outer surfaces. One end of the tube is closed, so that it can be inserted into the engine exhaust stream. Heat from the exhaust gas is relied on to activate the sensor ceramic tube. The sensor begins to operate for exhaust temperature in excess of 350°C. At this temperature, electrolytic conduction of oxygen ions occurs in the zirconia tube.

Sensor voltage is self-generated by electrochemical processes. Under ideal conditions, voltage output of the sensor is given by the Nernst equation where it is assumed that the exhaust-exposed electrode has sufficient catalytic activity to fully equilibrate exhaust gas chemical reactions.

The following features are inherent to the zirconia oxygen sensor:

(1) Rapid transient response-- approximate first-order time constant of 50 ms.

(2) Fast warmup time -- less than 30 s.

(3) Simple construction -- uses spark plug technology.

(4) Self-generated voltage output signal.

(5) Output signal is easily measured because signal strengths are hundreds of millivolts, and internal impedances are typically less than 10 kilohms.

(6) Stoichiometric air-fuel ratio is accurately measured -- accuracy typically better than ±0.3 ratio.

Humidity sensors are required for air-conditioning systems, particularly in demister applications. Humidity also plays a part in adaptive spark-advance (Ref. 10) systems as the amount of water vapor present effects the amount of knock-limited advance that can be used.

A direct measure of the mass flow of engine combustion air simplifies the control of air/fuel ratio (Ref. 11). It avoids the necessity to infer the amount of air entering the engine based on throttle position, manifold vacuum, and temperature. Mass flow is measured by a very low mass propeller (plastic foam) in one research system. The rotational speed of the propeller is a measure of the momentum of the incoming air stream.

Blunt body vortex-shedding devices which measure air velocity are also being investigated for automotive mass-flow purposes. The rate of vortex shedding is independent of temperature in these sensors, but true mass flow must still be determined analytically.

A bluff body, vortex-generating rod is placed in the intake air stream and the generated vortices are carried downstream of the rod. An ultransonic beam, with frequency of approximately 150 kHz, is transmitted across the flowing trail of vortex swirls. The flowing air carries the vortices through the acoustic beam.

Amplitude of the received ultrasonic signal is not constant, but rather, is modulated by passages of the vortices through the acoustic beam. Frequency of modulation of the received signal depends directly on the frequency of vortex shedding, whereas the modulation depth of the received signal depends on relative strengths of vortex disturbances. Since vortex shedding frequency is proportional to flow velocity, measurement of the frequency of modulation of the received acoustic signal gives a direct indication of air flow velocity.

The following features are inherent to the shedded-vortex air flow sensor:

(1) Wide, linear, 50:1 operating range -- typically 1.2 m/s to 60 m/s (11 cfm to 430 cfm through a 6.6 $in.^2$ duct).

(2) Good accuracy -- better than 1%.

(3) Good transient response -- detects flow changes as rapid as 570 m/s^2.

(4) Low pressure drop -- less than 0.4 kPa (1.5 in. H_2O).

(5) No moving parts.

(6) High operating temperature limit -- up to 425°C, allowing engine exhaust flow measurements.

(7) Digital output signal -- 150 pps to 15,000 pps, which is a direct indication of volume flow rate.

2. Systems

a. <u>Periodic Motor Vehicle Inspection (PMVI)</u>. Motor vehicle inspections on a periodic basis are conducted in 32 states. Additional states operate on a spot check system. These inspections are not uniform in scope, application, or standards (Ref. 12). The Clean Air Act of 1970 has given some emphasis to the establishment of periodic emission inspections (Ref. 13). Title II of this act provides that certain reductions of emissions be attained and also that the control devices have a useful life of at least 50,000 miles. It follows that sufficient inspections to be statistically significant are required to verify the performance.

Prior to the addition of emissions to the list of functions to be checked, vehicle inspections were intended primarily for the purpose of determining the overall safety of the motor vehicle. The test emphasis was primarily on braking system elements and performance, tire condition, suspension, and steering. Brake performance is based on a stop from 20 mph being accomplished within a certain distance (approx. 30 feet) or a floor mounted motor driven roller system is used to measure the braking torque available from the vehicle wheels (Ref. 14). Wheel removal is sometimes performed to measure both drum diameter and lining thickness or to ascertain disc-brake pad thickness. The flexible hydraulic lines to each wheel are visually checked as is the fluid level in the brake system reservoir. Mechanical parking brake linkages and cables are also visually inspected. Power brake systems are all inspected for leaks and pump drive belt condition. Pedal effort or "feel" and reserve is also inspected in some tests.

Suspension tests are primarily visual including the judgment of the amount of rebound present during a shock absorber jounce test. Steering wheel play is sometimes measured but more often felt. Tire and wheel play top to bottom and side to side is felt to judge wheel bearing and steering linkage looseness. This test also purportedly checks for ball joint wear.

Various miscellaneous visual inspections of lights, windshield wipers, belts, glass, and body condition are also performed. The functioning of wipers, horns, and lights are judged and sometimes the headlight aiming is measured.

The testing philosophy is based on the opinion that good maintenance will lessen the chance of accidents caused by equipment malfunction. A second philosophy not explicitly endorsed is that visual and subjective tests can in general determine both good maintenance and mechanical condition. This second point causes much controversy for the failure to provide the vehicle operator with a specific diagnosis of a fault or the part needing repair may cause unnecessary part replacement or hardship.

The two most populated countries in Arizona (Maricopa and Pima) have established automatic emission test inspection stations (Ref. 15) utilizing self-calibrated diagnostic equipment. These equipments are arrayed in multiple bays for each inspection lane. Twelve centers with a total of 36 inspection lanes are currently employed. There is also a mobile testing facility for the more remote residents of the two counties.

The tests measure and record unburned hydrocarbons and carbon monoxide at both low and high cruise speeds. The test requires 5 minutes and costs 5 dollars. A hard copy diagnosis and test result is furnished to the motor vehicle operator to assist in determining the reason for substandard performance. Reinspection, if required, is free.

A similar emission inspection station network employing diagnostic type equipment is scheduled for implementation in the Southern California area. The start of this program is scheduled for 1978.

b. Maintenance Indicator System. An instrument-panel-mounted indicator system called MIS (Maintenance Indicator System) (Ref. 7) was developed by Teledyne Continental Motors for the U.S. Army. The development was initiated in late 1971 by the Tank-Automotive Command for five-ton military trucks. The program was extended two years later to include the two-and-a-half-ton truck and the M60 tank. The MIS is part of the Army's Built-In Test Equipment (BITE) diagnostic-equipment development program. The purpose of MIS is to eliminate excessive periodic service and maintenance by indicating when a real need exists.

The MIS consists of an array of fourteen illuminated indicators (in the truck application) mounted in a panel together with the vehicle's speedometer, fuel gauge, upper beam indicator, and combined tachometer/elapsed-operation time indicator (see Figure 2). The light panel replaces the air brake and oil-pressure gauges. The indicators are grouped for fuel, oil, coolant, and brakes. There is a miscellaneous group for generator, battery, air cleaner, and transmission case temperature. The fuel functions monitored are pressure to the engine and differential drop across the fuel filter. The coolant is monitored for both low level and high temperature. The lube oil is measured for low level, low pressure, and excessive pressure drop across the filter. The air-brake system is monitored for low air pressure, low fluid and excessive pedal travel, and condensate in the compressed-air storage tank. The air cleaner for engine air is monitored for excessive pressure drop and also for the actual presence of a filter. The generator/alternator is monitored for output voltage and the battery for low voltage. The transmission transfer case is monitored for excessive temperature.

Each of the indicators is illuminated by two lights: an amber, indicating service is needed in the near future, and a red, indicating immediate attention is required. The lights are all actuated for a few seconds each time the vehicle master switch is turned on. The integrity of each wire and sensor connection is verified by other circuitry and the appropriate light is energized to warn the operator of the malfunction. The oil-level and coolant-level sensors are deactivated during engine operation to avoid spurious indications caused by fluid slosh or vehicle motions. Presence of the generator-output voltage disables these level sensors. There are lockouts on other sensors too. The filter sensors can only be reset by removing the filter retaining bolt.

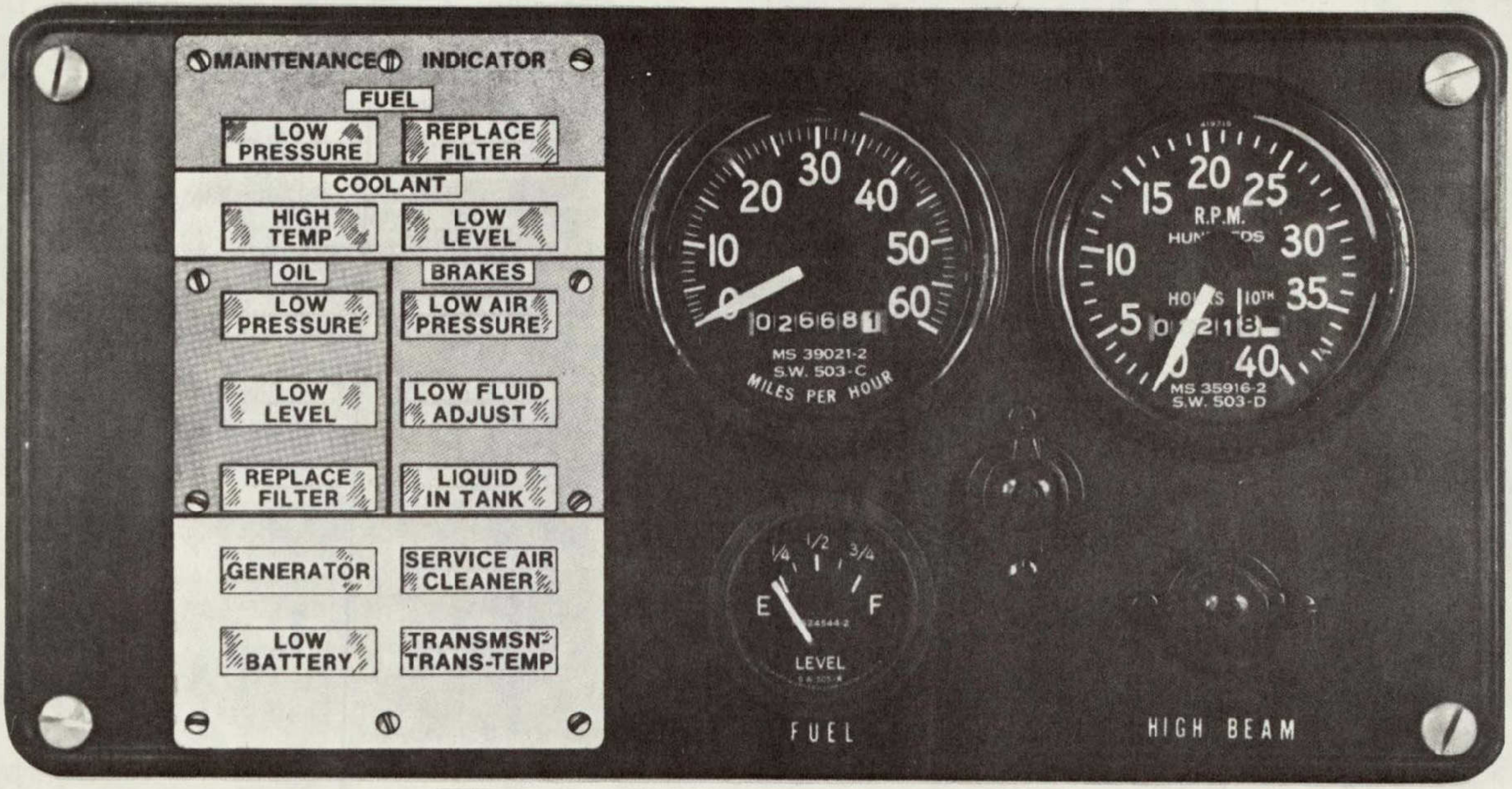

Figure 2. Maintenance Indicator System Panel

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The oil-filter sensor is also not activated after resetting until the oil temperature reaches 100°F.

The various sensors are essentially independent except for the interactions mentioned before. There is no unifying circuitry to conclude probable causes for multiple indications such as might be the case where a radiator-cooling-fan belt breaks and the generator light comes on followed shortly by the coolant high temperature light.

Table 1 is a listing of the MIS functional measurements and the operating limits and tolerances.

Table 1. MIS Measurements

Function	Limits
Oil filter restriction	12 ± 2 psi differential
Fuel filter restriction	15 ± 2 psi differential
Air filter restriction	27 ± 15% in. of water
Engine oil pressure	6 ± 2 psig
Engine oil level	Gage rod add level ±0.12 in.
Vehicle fuel pressure	1.5 ± 0.5 psig
Coolant temperature	225 ± 5 deg F
Transmission temperature	275 ± 5 deg F
Transfer case temperature	275 ± 5 deg F
Radiator coolant level	0.83 ± 0.12 in. below full line
Vehicle air pressure	65 ± 2 psig
Brake fluid level	1.62 ± 0.12 in. below full
Brake adjustment	Pedal position 2 in. from full travel
Air reservoir water detection	945 cc (static)
Generator output	Generator charge > 6 volts
Battery voltage	> 18 volts

c. <u>OK Monitor (Electro Sensor Panel)</u>. The OK Monitor, first introduced on the 1973 Toyota, is a driver information diagnostic panel which monitors various operational functions (Ref. 16). The system utilizes 16 different sensors and provides detection of 11 items. This individual warning light system illuminates a part of the panel identifying the fault and a red flashing light attracts the attention of the driver. Almost all of the sensors are switches indicating a limit has been reached by the change in continuity. Relays are used to sense the current drain of a functioning lamp with the relay contact providing the sensing function if a lamp is open-circuited.

The conditions tested by the OK Monitor are:

(1) Brake pad wear.

(2) Coolant temperature.

(3) Oil level.

(4) Brake fluid level.

(5) Reservoir tank level (brake fluid).

(6) Battery electrolyte level.

(7) Washer fluid level.

(8) Vacuum warning (excessive fuel consumption).

(9) Lamp failures.

(10) Blown fuses.

A switch opening is used to indicate a fault, therefore a wiring or connector fault will be indicated as well as the malfunction.

d. <u>Autosense</u>. Autosense, manufactured by Hamilton Test Systems, is a computer-based diagnostic instrument used to determine automobile malfunctions. The Autosense system (see Figure 3) by means of various parameter measurements and a comparison of these measurements against certain limits, identifies probable malfunction causes (Refs. 17 and 18).

The Autosense system consists of a vehicle harness which includes the sensors and connections required to test the engine performance, the ignition system, the charging system, and the cranking system. These sensors and connection points are:

(1) Vehicle ground.

(2) Plus battery.

(3) Minus battery.

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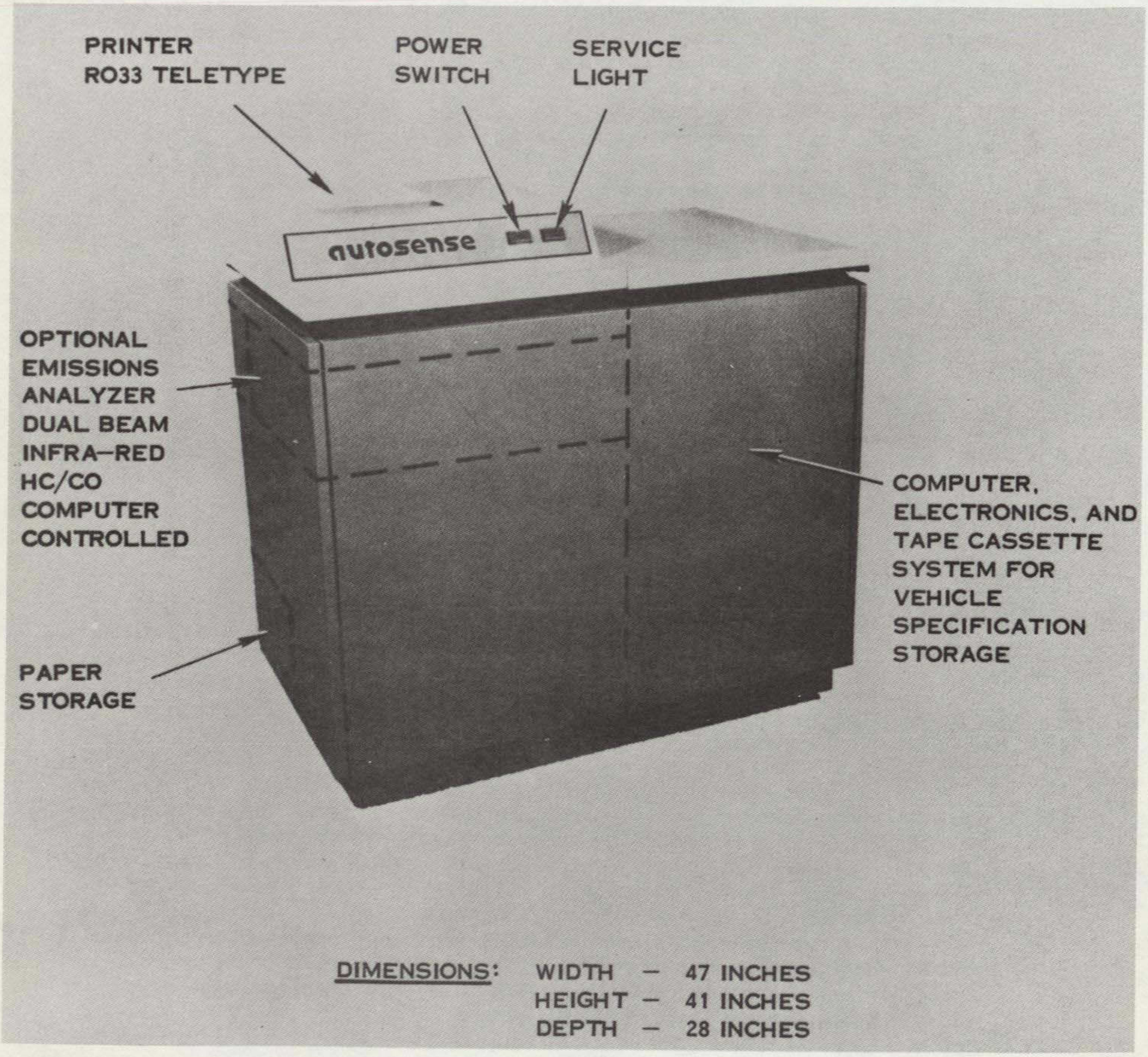

Figure 3. Autosense Console

(4) Clamp-on current probe.

(5) Timing pickup (Top dead center magnetic pickup or timing light).

(6) Starter solenoid coil.

(7) Starter solenoid contact.

(8) Starter motor.

(9) Alternator field.

(10) Alternator output.

(11) Voltage regulator field.

(12) Voltage regulator battery.

(13) Ignition coil (battery side).

(14) Ignition coil (points side).

(15) Ignition coil secondary.

(16) No. 1 spark plug.

(17) Intake manifold pressure.

(18) Tailpipe sensor.

The connections are shown schematically in Figure 4. From the foregoing list it is apparent that most of the measurements taken are voltages at various points. Battery current is an exception. Battery drain is measured by a Hall effect clamp-on device which has two automatically selected ranges: 0-50 and 0-300 amperes. A 200 mv shunt is used for other current measurements. Engine timing is measured from the output of a magnetic pickup which senses the TDC notch in the vibration damper or a timing light with adjustable timing delay. This allows the operator to line up the timing marks by adjusting the time of the strobe flash and establish a TDC reference for subsequent tests. The high-voltage measurements are made by in-line capacitive voltage dividers placed in series with the high voltage leads at the distributor cap. A strain-wire-bridge low pressure (0-20 psi) gauge is used to sense the manifold vacuum. A nondispersive infrared type of emission analyzer is used to convert the HC and CO measures to electrical outputs. The analyzer has both pressure and temperature compensation for automatic zeroing and span adjustment. The pump control and the detection of blocked filters and linearization of the measured value are automatic. The gas analyzer and vacuum sensor are mounted in the Autosense console and connected by tubing to the vehicle.

The various measurements are filtered to avoid electromagnetic interference and are then multiplexed by analog switches to a common

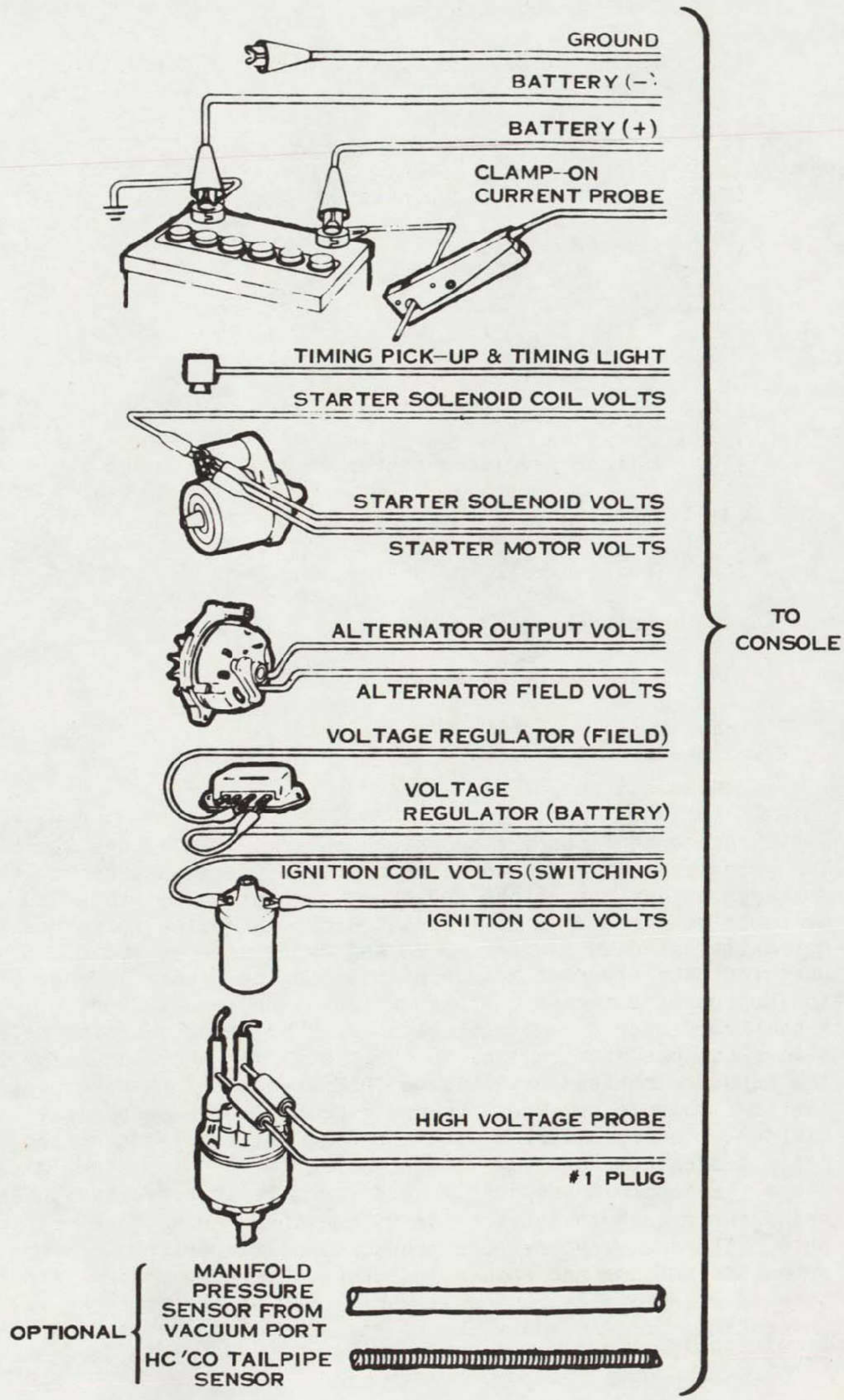

Figure 4. Vehicle Harness Connections

12-bit analog-to-digital converter. The top-dead-center probe or timing light input as well as the coil primary (point opening and closing or transistor switch) and the number one plug voltage are input as times of occurrence by means of start/stop circuits and pulse width to digital converters. Another set of inputs are derived from the electrical outputs of the hydrocarbon and carbon monoxide emission analyzer and are also multiplexed into the 12-bit analog-to-digital converter.

All of the digitized measurements are converted to serial words and supplied to a 16-bit serial computer. The computer has 4100 words (expandable to 8200 words) of random access memory for the diagnosis and parameter comparator programs.

The operator of the Autosense is required to enter vehicle identification data through the hand held control (see Figure 5). This control has a ten-digit keyboard and seven other function keys. Three separate numerical displays present the reference test number, data, limits, instructions, and real time selected measurements to the operator.

A tape cassette and reader are also part of Autosense. This cassette contains manufacturer's reference data for the various measurements, as well as provided or deduced limits for these measures. Data for 5 years past of domestic cars, updated at six month intervals, are available. Similar data are available for the most common foreign automobiles.

After vehicle identity entry, the appropriate cassette is searched and the specification limits are transferred to the computer memory. The diagnosis is initiated by the operator first entering a code for the particular complaint. The operator is then cued to conduct certain tests involving static key-on, cranking, idling, run-up, and fast idle modes. The results of the tests as well as the high and low limits are printed out as a hard copy vehicle test report (Figure 6). Repair codes are also printed out indicating probable required repairs. The system also allows re-entry to any of the diagnostic tests after repairs have been done to determine if the out-of-limit condition has been corrected.

The Autosense is intended to be used for tune-ups and periodic maintenance as well as for customer complaints and predelivery preparation. Hookup through complete printout requires some 12 to 15 minutes in the tune-up or maintenance check mode. The measurements, scales and accuracies are shown in Table 2.

e. Diesel Diagnostic System. The Diesel Diagnostic System, or Diesel Sense, also manufactured by Hamilton Test Systems, is an adaptation of Autosense for the checkout of compression ignition engines. The same operator control, console and printer, and essentially the same vehicle or engine harness are used in Diesel Sense as in Autosense. The computer memory is expanded to the full 8192 words and additional tests are provided which are peculiar to diesel engines. Most of the tests that are only associated with spark ignition are eliminated, but provisions are made for glow-plug tests on diesel engines that use these for starting.

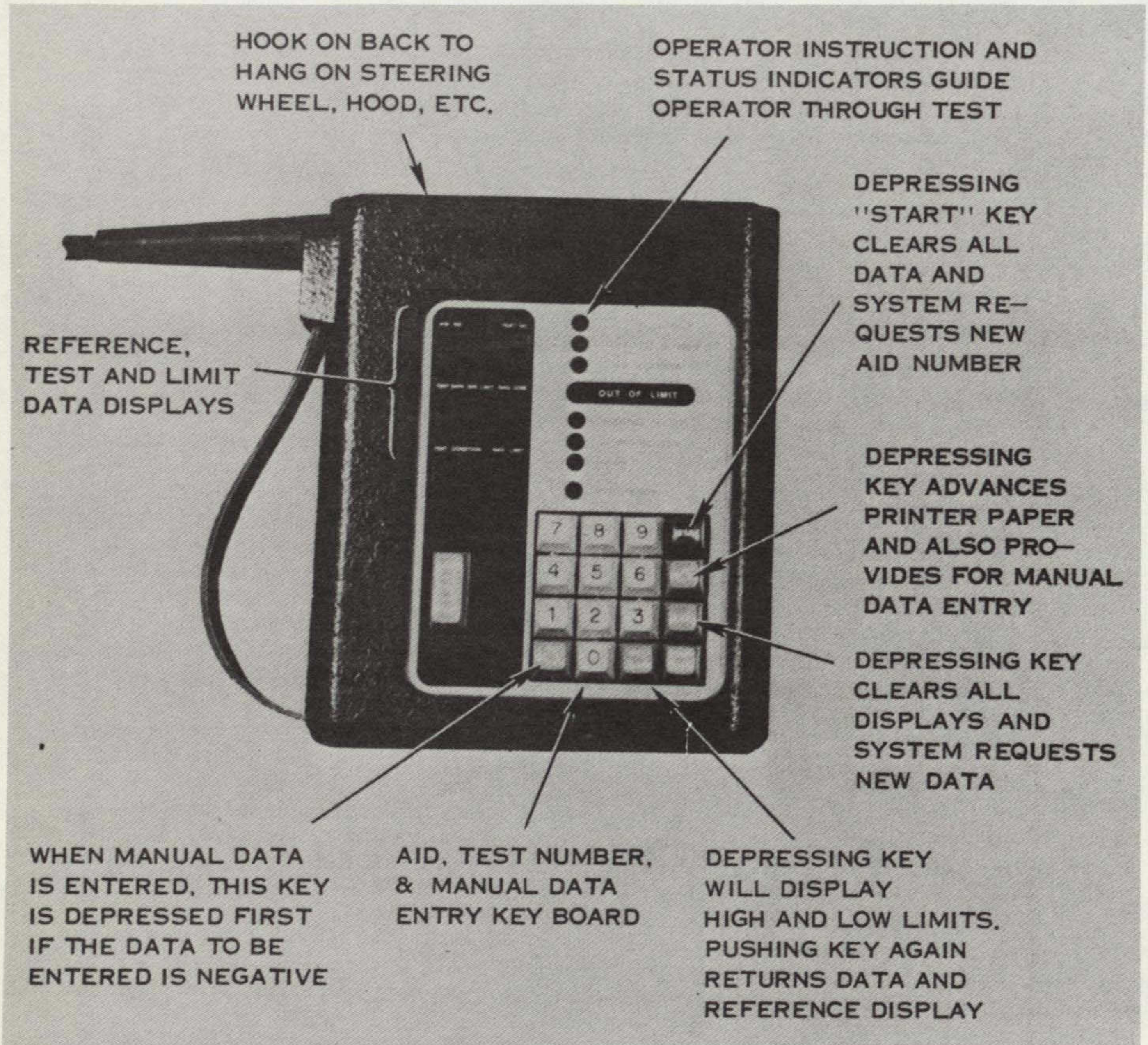

Figure 5. Operator's Hand Held Control

The diesel tests require eight additional pressure measurements in the 0-30 and 0-300 psig range. Separate gauges are not provided, but the pressure lines from the engine are multiplexed to one gauge by means of solenoid valves. The pressure line connections dominate the hookup time, requiring 45 minutes on an engine without quick disconnects. This time is reduced to 15 minutes on engines with quick disconnects. The lines conveying hydraulic pressure to the sensors such as fuel and lube pressure are automatically bled prior to testing.

Table 2. Autosense Measurement Specifications

Current	10.1 - 50 Amp 50.1 - 300 Amp	±0.75 Amp ±6.0 Amp
DC Voltage	0-20v	±0.2v
Kilovolts	(0-50 kv)	±10%
Rpm	(0-7000 rpm)	40-700 rpm ±20 rpm 700-3200 rpm ±3% of reading 3200-7000 rpm ±10% of reading
Dwell		100 to 2500 rpm ±1°
Timing (using magnetic pickup)	(-20° - +60°)	100 to 2500 rpm ±1°
HC (0-2000 ppm)		±3% FS
CO (0-10%)		±3% FS
Pressure	0-17 psia	±1.5% FS
Warm-up Time		10 min
Response Time		10 sec (To 90% of reading)

The Diesel Sense differs from Autosense in that a direct measure of the relative power contribution of each cylinder is made using the rotational inertia of the engine as the load. This measure requires that the instantaneous rotational velocity of the engine be measured and correlated with each piston power stroke. A magnetic pickup placed next to the starter ring gear on the flywheel provides this measure. The power contribution measurement is made by rapidly accelerating the engine from idle to maximum "throttle" several times. The rate of angular velocity increase provided by each cylinder is averaged to determine the relative power output of each cylinder. Figure 7a depicts the angular rotation or speed curve versus time during "run-up". The discontinuities on the curve indicate the acceleration contribution of each cylinder. Figure 7b depicts the same curve with cylinder No. 3 defeated and, therefore, not contributing power. Instead of the acceleration expected, there is actually a deceleration, since cylinder No. 3 is a load on the crankshaft rather than a power contributor.

Other tests peculiar to Diesel Sense are: blow-by which is measured by noting the pressure fluctuations at the crankcase filler pipe; turbocharger boost pressure and drag; injector timing; and, fuel pump calibration.

Diesel Sense is used in the complaint-oriented mode as well as the tune-up or preventative-maintenance mode. Another planned use is a quality control check at the end of engine assembly lines.

f. <u>Avis Autosense System</u>. The Avis Autosense System is a modification of the basic Autosense to orient the device toward a more automatic screening mode rather than a diagnostic mode (Ref. 19). The needs of Avis as a large volume purchaser of new cars and vehicle renter are for a rapid means to check new cars on delivery and ascertain whether preventative maintenance is required on returned rentals.

The conventional Autosense, according to Avis, was too slow for their needs. The need was for a system which would proceed automatically from one test to the next without waiting for printing of intermediate results. Avis has contracted with Hamilton Test Systems for Autosense units with increased memory size, modified software, and wider test limits.

The wider limits were found necessary to provide the necessary vehicles to satisfy customer demand. Avis found that if new cars were screened to manufacturers specifications and tolerances, about 85% would be rejected, primarily for idle speed or timing adjustment. To avoid the delays in having the out-of-tolerance conditions corrected, wider limits provided a still driveable vehicle with less than optimum performance. The rejection rate was reduced to 45%. Regardless of the limits, the Autosense printouts provide a permanent record of the vehicle parameters, when delivered, which may be used as the basis for post delivery negotiations and possible warranty adjustments.

The new vehicle (less than 1000 indicated miles) checkout involves some fourteen tests of the engine, ignition, charging, engine electrical, and emissions. These are all standard test sequences, but in some cases the tests have been abbreviated. If the odometer indicates more than 1000 miles, then additional tests are performed. These are the relative compression and the cylinder power contribution tests. Entering the mileage together with the vehicle ID at the start of the test determines the sequence to be utilized.

The goal for Avis is a 5-minute checkout including sensor hookup and the printout of results. The current minimum time achieved is 3 minutes and 5 seconds. This time may be compared with the minimum that

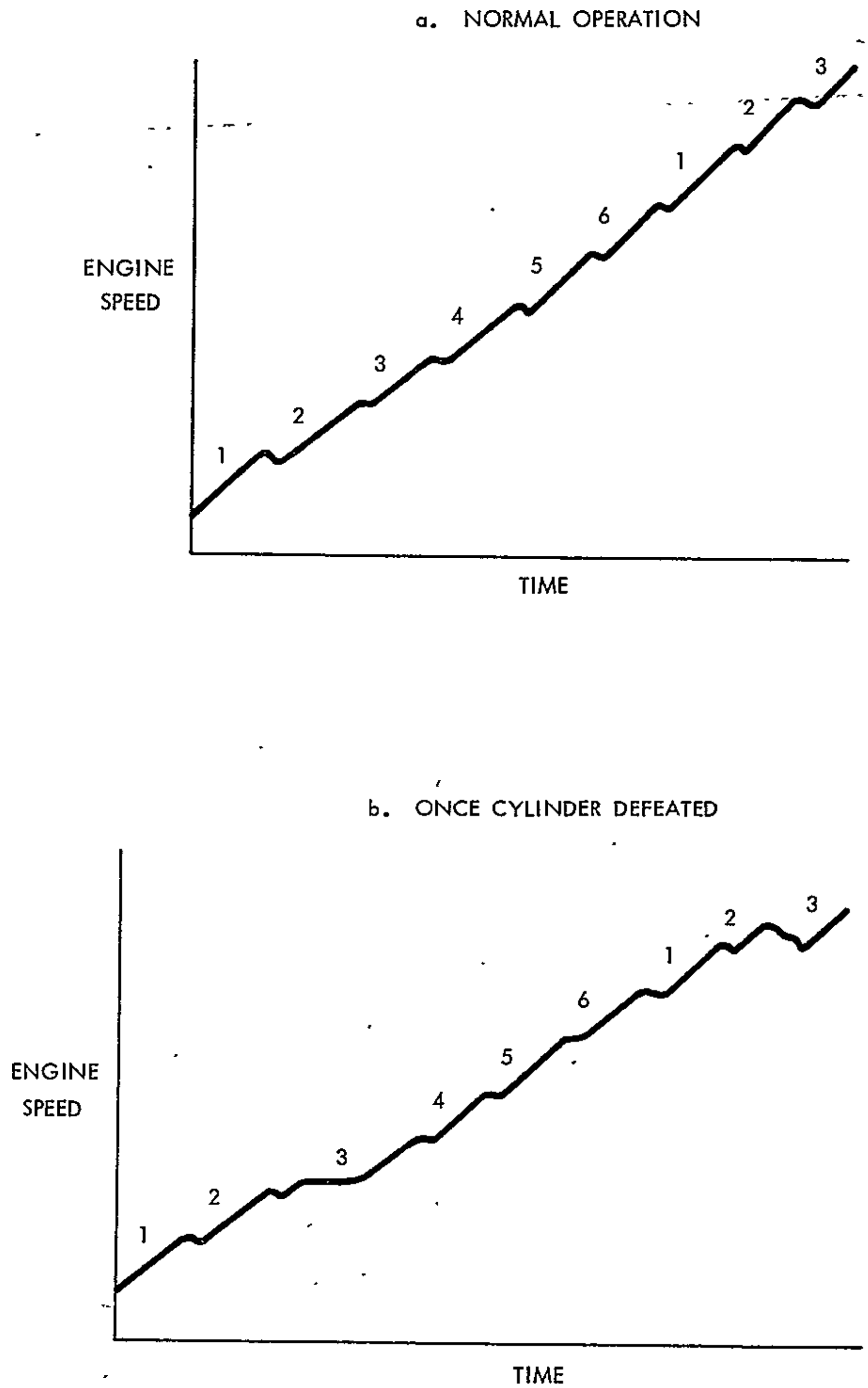

Figure 7. Diesel Speed Time Curves, No Load

Avis mechanics could achieve with conventional oscilloscope-based test equipment; some 25 minutes. The test sequence is briefly as follows:

(1) Key on.

(2) Cranking - Compression check by means of starter current.

(3) Start and Idle - Makes series of 40-second timing, mixture and alternator tests.

(4) Run up to 2500 rpm - Additional ignition, timing and emission tests. Power contribution test.

(5) Automatic shutdown - Printout of results.

The checkout prints data on the performance of the car as received. If there is an idle speed or timing adjustment called for, these can be made without calling for diagnostic tests and a checkout test rerun. Other software changes were a reduction of the power contribution test from 20 seconds per cylinder to 8 seconds each. The use of heavy fly-wheels by some manufacturers tended to cause a failure indication on this test even by properly operating engines and software changes to widen limits were required. The original test sequence also called for a battery available voltage test immediately after cranking. The test at this time gave a spuriously low value for battery voltage so the test time was changed to the end of the idle test; this yielded a more realistic value. Prior to the actual sensor check of the vehicle; the operator enters data derived from visual checks. These may include tires, drive belts, body dents, missing equipment, and glass condition. These visual check data then become part of the printed record.

The Avis Autosense units are to be equipped with tape cassette recorders to enable the gathering of statistical data. Each of the test results will be tape recorded at the individual Avis installations together with suitable annotation data; date, time, etc. The tapes will then be forwarded to Avis Headquarters for statistical compilation. This procedure should allow preventative repair and maintenance strategies to be established in response to discover failure or malfunction trends.

At present, Avis has units in the four largest markets undergoing evaluation tests. These are San Francisco, Philadelphia, Chicago, and New York.

g. Avis Red Box. Prior to Autosense, Avis had experimented with a vehicle checkout system called the "Red Box." This was a drive-through unit which tested such things as brake performance and lights. The tread depth of the tires was automatically checked at three points on the tire footprint. Multiple spring loaded fingers probed the tread pattern at each point. The difference in penetration was electrically measured. The characteristics of these sensors limited the speed of the vehicle to less than 3 to 5 miles per hour. A tire pressure sensor was also included. This was a circular plunger that the tire passed over which then measured the pressure per unit area of the tire footprint. This device was found to be less accurate than desired. Tread thickness for example, had a significant effect. The differing stiffness of thicker and thinner treads in bridging from the roadway to moveable sensor plungers caused substantial errors in the readings.

A drive over toe-in indicator was also available in the system at an additional cost.

The "Red Box" required 18 manual inputs in order to run the tests. It was a large unit, physically too big to be installed indoors with the result that there were many operational difficulties. Many of the observations relied on mirrors which clouded-up because of condensation at night. The throughput of the device was slow with the result that an operational bottleneck was created. The operational difficulties forced the abandonment of the device even though most of the technical concepts were and are sound.

h. Bus Maintenance System. The BMS 1000, manufactured by PRD Electronics in Westbury, New York is a computer based diagnostic system that measures and judges the various systems (Refs. 20 and 21) common to intra and inter city buses. The BMS 1000 in passenger bus application makes 58 measurements of the electrical, engine, air conditioning and heating, air supply and brake, and transmission-converter systems (Ref. 22). The system is intended for use in the periodic maintenance inspection of buses to detect and indicate faulty or out of limit conditions. The system can also indicate needed repairs and verify in-limit performance after repair has been accomplished.

The BMS 1000 is contained in a single cabinet (see Figure 8). In the top of the cabinet is a hard copy printer to provide a permanent record of the results of the tests. The front panel contains a two-line alphanumeric display to lead the operator through the tests by instructions and to provide data to the operator. There are also various operational push buttons to step through the tests, clear data, or reenter the test sequence. Hazard indicators are also located on this panel together with an audible alarm. These are to provide immediate action warnings of out-of-tolerance conditions that could cause severe damage to the systems under test. The front of the cabinet contains drawers where the various sensors and adaptors for different bus equipments are stowed.

The cabinet is connected by a sensor harness to the bus equipments. In this system, the pressure and vacuum sensors are all located at the engine or equipment under test and all connections to the cabinet are, thereby, electrical. The pressure and temperature sensors are connected to the appropriate points by quick disconnects or at leak-proof insertion points. This technique avoids the necessity of bleeding lines, but does subject the expensive pressure and temperature transducers to considerable handling.

The sensors used are platinum resistance thermometers, strain-wire-bridge pressure gages, and magnetic proximity sensors for rotating elements.

Numerous voltage points are measured by clip-on leads and current measurements are made with both Hall effect and resistance shunts.

The outputs of the sensors are conditioned and filtered prior to analog-to-digital conversion. They are also scaled with programmable gain where required. The data are accumulated and supplied to a 16-bit microprocessor with 2000 words of read-only-memory and 8000 words of random-access-memory.

In addition to the computer memory, a tape cassette is employed as bulk storage. The cassette data includes the self-checking sequence and the test and diagnosis programs for the various bus subsystems. Also included are the reference or standard values for the various measurements as well as the high and low limits. These values as well as the destination of sensed data in the computer and scaling factors are different for different engine and other subsystem configurations. The correct values are established by the operator entering a two digit

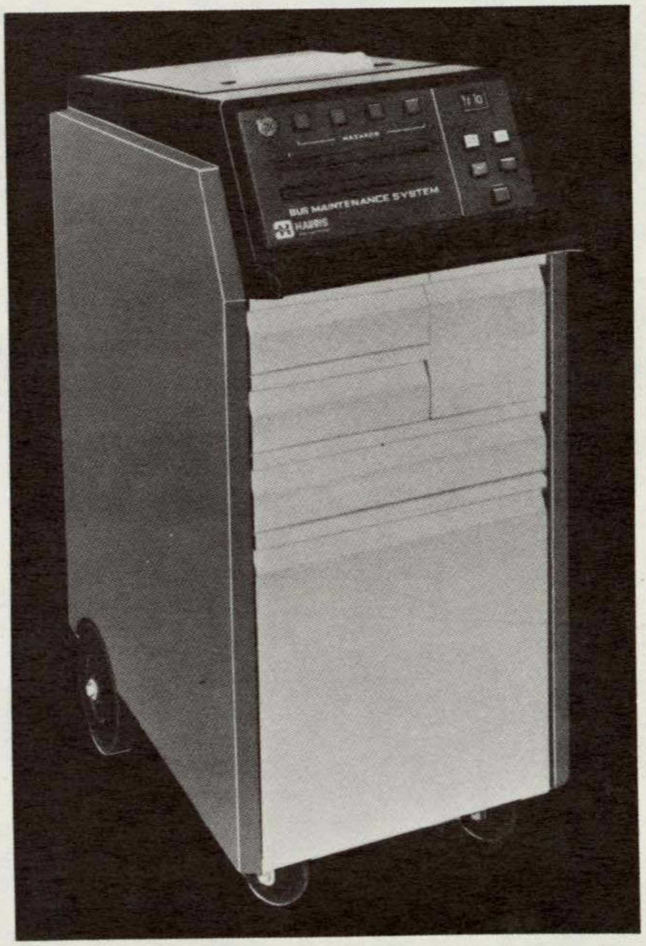

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Figure 8. BMS 1000 Bus Maintenance System

identity number at the start of the tests. Other software on the tape includes fault patterns for diagnosis and the applicable diagnostic messages for the operator. Operator instructions are included on the tape. They are displayed to lead the operator through the tests.

Future plans for the BMS 1000 include the addition of a hand-held two-line display and keyboard. This unit may be carried by the operator while making visual inspections and can serve as an indicator displaying pertinent measures when making adjustments.

i. Integrated Digital Engine Analyzer. IDEA is an acronym for Integrated Digital Engine Analyzer. It is an outgrowth of the same technology which is used in the BMS 1000 (Ref. 23) and it is also a product of the PRD Electronics Division of Harris Corporation (Ref. 24). IDEA is a portable unit contained in two units (see Figure 9) and will operate from line or automotive battery voltage. The portability allows IDEA to be carried to marine and other non-traction diesel engines.

IDEA relies on a tape cassette to store parameters and programs for different engine types and operational sequences.

Relative cylinder compression and balance and relative power contribution of each cylinder are measured and displayed. Compression is measured by starter current draw as in other systems. Power contribution is determined by measuring the rate of change of angular velocity at the flywheel and correlating it with each piston power stroke. The measurement is taken during no load run-up and averaged over several accelerations. Other tests are made of the lube-oil pressure and temperature, cooling, fuel pump pressures, electrical starting and charging, brake air, turbo-charger, and combustion air.

The results of the tests together with probable fault diagnosis is made and printed on hard copy. The operator interface unit is a hand-held two-line display with keyboard.

The accuracy of the measurements are:

(1)	Pressure	±2% of range
(2)	Current	±2% of range
(3)	Temperature	±2% of reading, or +2°F
(4)	Voltage	±1% of range
(5)	Speed	±.1% of range or ±3 rpm

j. Simplified Test Equipment - Internal Combustion Engine. The Simplified Test Equipment-Internal Combustion Engine (STE-ICE pronounced "stay-ice") (Ref. 25) is a U.S. Army-sponsored system currently in Low Rate Initial Production status, and is being produced by RCA (Figure 10). The development of STE-ICE was undertaken during the development

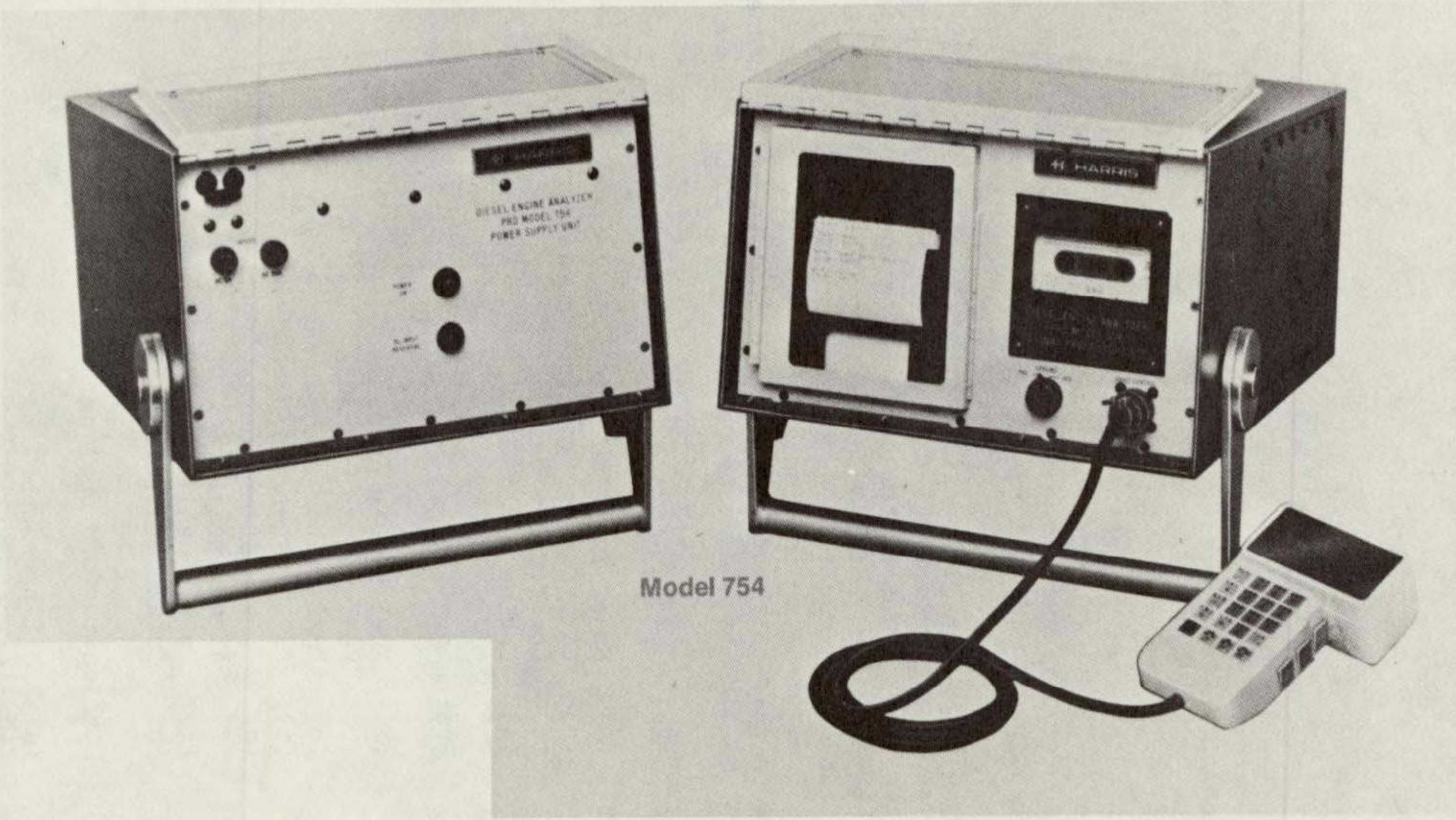

Figure 9. IDEA System

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of ATE-ICE (Automatic Test Equipment-Internal Combustion Engine), a more complex and automatic system. Both of the test equipments are computer-based diagnostic units intended for low-echelon (field and motor pool) use in the servicing of Army motor vehicles. The objective of the developments is to "make diagnosis by testing easier and faster than diagnosis by parts replacement." (Ref. 26)

Three units make up the STE-ICE system. These are: the vehicle test meter (VTM), which is a small box (approximately 12 in. x 9 in. x 7 in.) weighing 11 lb; a transducer kit consisting of several pressure and temperature sensors, clamp-on current probe, and voltage point clips; and an interconnecting cable or diagnostic connector assembly.

For those vehicles that have previously been fitted with transducers, a dash panel connector is available which allows the vehicle test meter (VTM) to be connected in short order by means of the cable. The transducer kit must be used on unequipped vehicles and substantial time is required to fit all of the sensors.

The STE-ICE can be used to test at least 11 different types of Army vehicles ranging from the M60 tank down to the jeep-size M151A2-series quarter-ton truck. The system can also be used on the commercial trucks and on the passenger vehicles used in supply and staff applications. The tests and measurements are focussed on the engine power and compression, fuel/air, lubrication and cooling, starting and charging, and ignition. A self-test mode is also included to verify proper STE-ICE operation. A list of the tests made in these areas follows:

(1) Engine

(a) Spark ignition (gasoline) power test
(b) Compression ignition (diesel) power test
(c) Compression balance
(d) Engine r/min

(2) Fuel/air

(a) Fuel supply pressure
(b) Fuel return pressure
(c) Fuel filter pressure drop
(d) Air cleaner pressure drop
(e) Turbocharger outlet pressure
(f) Airbox pressure
(g) Intake manifold vacuum
(h) Intake manifold vacuum variation

(3) Lubrication and cooling

(a) Oil pressure
(b) Oil temperature
(c) Coolant temperature

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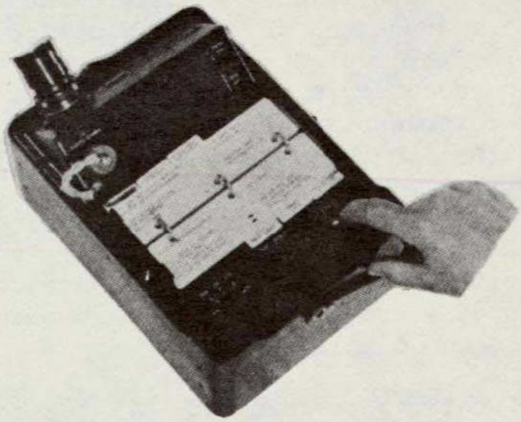

Figure 10. STE-ICE Unit

(4) Starting/charging

(a) Battery voltage and current
(b) Battery electrolyte level
(c) Starter voltage and current
(d) Starter current, first peak
(e) Starter ground cable voltage drop
(f) Alternator/generator output voltage and current
(g) Alternator/generator field voltage and current

(5) Ignition

(a) Dwell angle
(b) Points voltage
(c) Coil primary voltage/resistance
(d) Timing

Instruments that are replaced by the STE-ICE include a multimeter, tachometer, low-voltage circuit tester, dwell meter, vacuum gauge, compression gauge, and assorted pressure gauges. The vehicles test meter is small enough that it can be placed at various spots on the vehicle and provide a near-at-hand display of a parameter being adjusted or measured. While not as portable as the hand-held units, it serves the intended purpose quite well.

The microprocessor (CPU) used in the STE-ICE is a Rockwell International PPS-4. In addition to the CPU, there are 512 four-bit words of "scratchpad" (or random-access memory) and 1536 eight-bit words of programmable read-only memory (PROM) for constants, as well as 4096 eight-bit words of PROM for program storage.

The control function and computations performed include a determination that the test number called for is valid for the vehicle under test. On vehicles equipped with the dash-panel connector and transducers, there is an identifying resistance included in the wiring harness. Automatic measurement of this resistance identifies the vehicle to the VTM and thereby prevents the operator from calling for improper tests. The microprocessor establishes the routing path of the measurements through the various signal conditioners, filters, analog-to-digital conversion, and then to the appropriate memory location. It also determines if a single measurement or series of samples is to be made. The computer averages measurements where required and establishes the timed interval between measurements, as well as programming gains to adjust the scale of the measurements. The values sampled are compared against limits and, where needed, the measurement is converted to engineering units for display.

The test functions performed by STE-ICE on either spark or compression ignition engines lead to the display of a value or condition in most cases. The sequential or logical steps to be made in going through a diagnostic tree are not performed automatically. The operator has printed instructions for each test series, permanently attached to the VTM, which contain proper intermediate test results and procedural steps. The test steps have to be followed in the proper fashion to successfully complete a test.

There is one test that is unique to STE-ICE. This test is a determination of the percent of full-rated power output of a spark ignition engine. The test is made at full throttle and by means of systematically eliminating the sparkplug firing voltages, a much-reduced maximum "no-load" speed is attained. This reduced speed has been determined by dynamometer tests to accurately reflect the full output power of the engine. The power from each cylinder is pitted in turn against the inertial load of the engine and the load of the compression and exhaust strokes of the other unfired cylinders. This technique, in a sense, allows the remainder of the engine to act as a dynamometer for the functioning or power-producing part.

On a four-cylinder engine, four out of each five spark-plug firings are eliminated. There are normally two power strokes per revolution, but this elimination reduces that to one power stroke every two revolutions. The speed is greatly reduced because of this loss of power strokes and because the other cylinders are compressing full charges without throttle losses.

Typical speeds that might be attained for a four-cylinder quarter-ton-truck engine are in the 1100 to 1400 rpm range for acceptable power output. Acceptable power has been determined to be 75 percent of full rated power. The 75 percent value was obtained by a series of tests using a large group of drivers familiar with the vehicles. The vehicles were detuned to various power levels and the drivers, who were unaware of this, were asked to comment on driveability. Some drivers could detect small losses of power, but, in general, the vehicle performance was unsatisfactory to all when the 75 percent level was reached.

SECTION II

GUIDANCE TECHNOLOGIES

A. INTRODUCTION

Automated highways, high-speed ground transit, guided transit, and personnel rapid transit all share the requirements for lateral and longitudinal guidance and control. Purely mechanical (e.g., tracks) or other lateral guidance techniques requiring no steering on the vehicle will not be addressed here. The longitudinal control refers to the means of maintaining speed and/or position on the right-of-way. Speed control and on-board headway sensors are part of the longitudinal control but will be discussed separately as will the automotive elements required for lateral control.

B. LATERAL GUIDANCE

The techniques for lateral guidance employ magnetic, electromagnetic, optical, acoustic, and very high frequency radio technologies. The most common technique in current use, is the "buried wire" used to guide very slow moving vehicles in warehouses, storage yards, hospitals, etc.

The buried wire has been the foundation of many experimental guidance studies employing passenger automobile and buses; the former at speeds greater than 100 km/hr.

1. Single Buried Wire

This technique employs a single wire, buried in a shallow groove, usually along the center line of a highway lane or the vehicle right-of-way. The term "single wire" means single loop as the wire used in a lane returns by another lane to form a Loop. Similarly, in warehouse operations and the like, a complete circular route or loop is desired and the single-wire loop describes the complete path.

The wire is excited with low frequency alternating current. The frequencies employed are generally less than 10 kHz where FCC licensing is not required. Several loops covering different routes can share a common section of right-of-way by using different frequencies. The vehicles intended for the different routes then discriminate among the different frequencies to determine which wire should be followed.

The power required to energize the wire is usually modest with currents of about 1 A being typical. Large-gauge wire is usually used for mechanical strength and the inductance of the wire is the predominant impedance. The loop is often tuned with capacitance at the generator to make a series resonant, albeit low Q, circuit.

The lines of equistrength magnetic field around the single wire are essentially concentric circles if the return wire is distant. When the wires are close together (e.g., less than a few meters), the lines of equal strength are no longer concentric but are circular with the centers displaced away from the wires as depicted in Figure 11a. The effect of this lack of symmetry above the wire is to introduce a yaw component if the vehicle sensor-to-wire distance changes, as in bounce and rebound.

Yaw motions are also introduced by distortions of the magnetic field. These distortions occur where the wire passes close to a ferrous mass such as a manhole cover, or bridge deck, or the reinforcing steel in concrete road surfaces.

Two types of sensors are used to provide the steering signals required to follow the wire. These are amplitude comparators and phase sensitive detectors.

The amplitude comparator consists of two coils, one each side of the wire, as in Figure 11b. As either coil moves toward the wire, the signal amplitude increases while the other coil output diminishes. The algebraic sum of the signals develops a right or left turning signal to cause the amplitudes to become equal by centering the sensor coils over the wire.

Amplitude sensors are usually positioned quite closely to the wire and as a consequence the application is limited to slow moving vehicles. The sensor is also sensitive to amplitude variations which are caused by distortions of the field as mentioned before.

In an attempt to avoid some of the effects attributable to amplitude variations, a guidance sensor sensitive to only the phase (direction) of the magnetic field was developed. This technique measures the relative phase of the vertical component of the field on each side of the wire with a linear array of vertically oriented coils (Figure 12a). A horizontal coil provides a reference signal to a group of phase detectors, one for each vertical coil. The outputs of the phase detectors are either high or low depending on whether the inputs are in or out of phase. Each of the phase detector outputs is the input to the junction of a summing amplifier. The junction is biased so that the amplifier output is zero when there are an equal number of high and low phase detector outputs. The summing amplifier output is a stepwise signal proportional (Figure 12b) to the amount of offset either side of the wire; positive on one side and negative on the other side of the wire.

Experiments with the phase type sensor have indicated less than 1-1/2 cms lateral offset at speeds up to 120 km/hr. It has also been determined experimentally that this type of sensor is relatively insensitive to the field concentrations caused by ferrous masses next to the wire.

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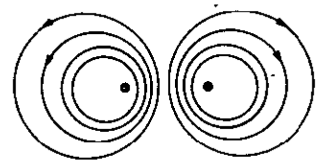

Figure 11a. Magnetic Field Lines

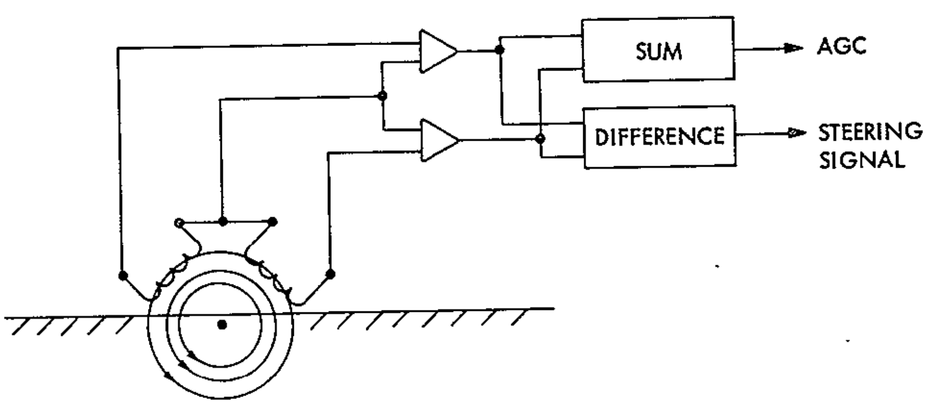

Figure 11b. Amplitude Sensor Coils

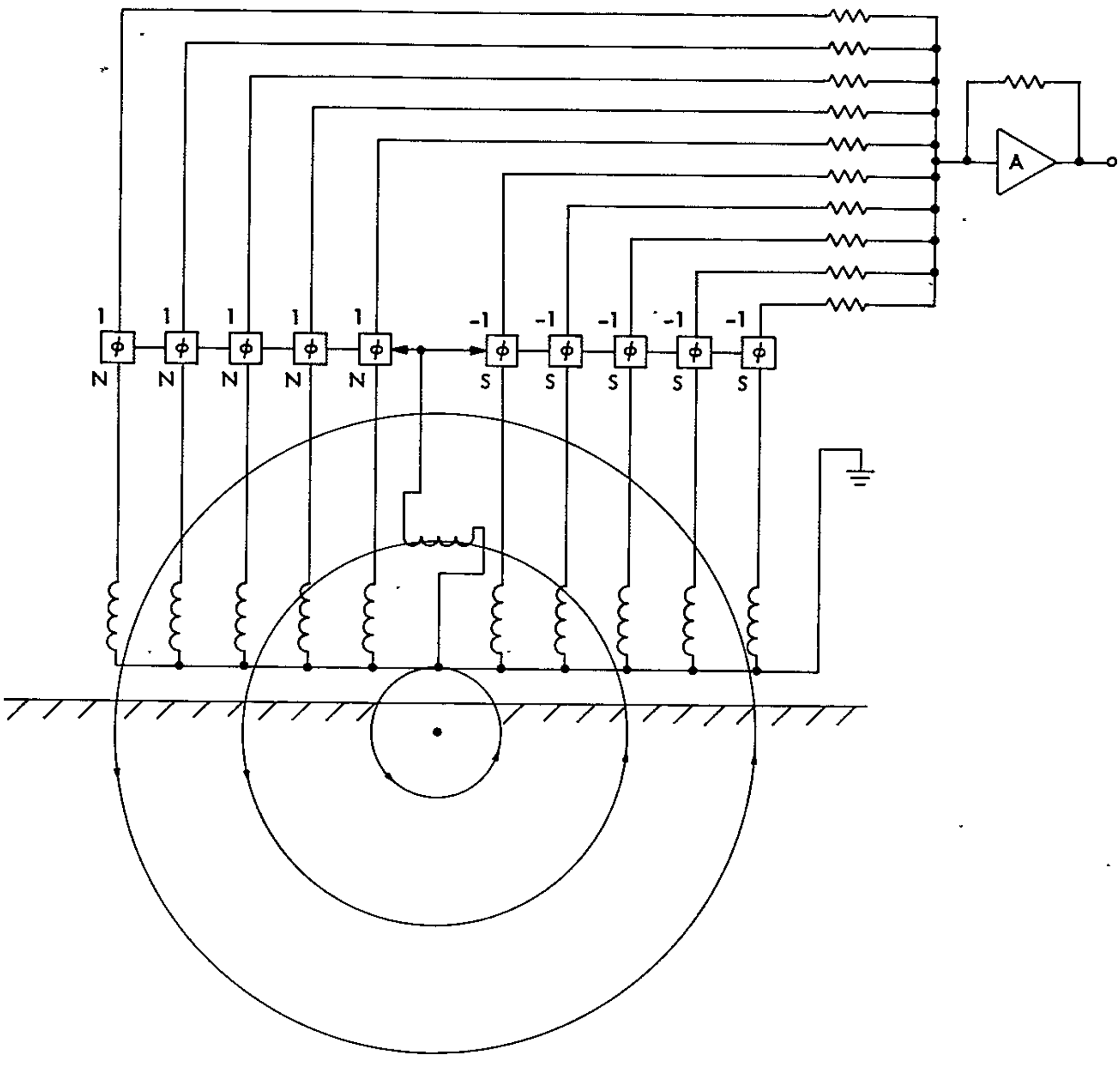

Figure 12a. Phase Sensitive Detector

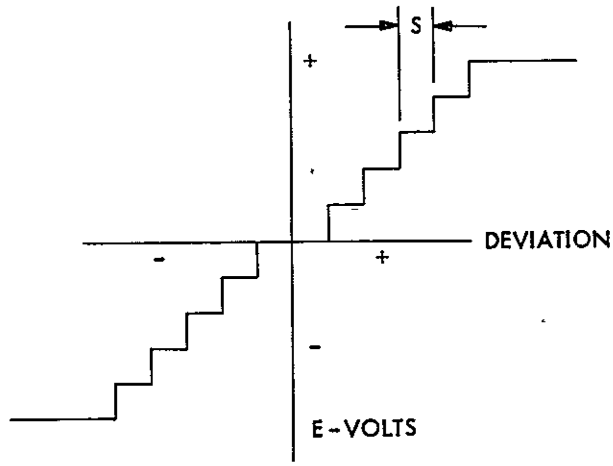

Figure 12b. Proportional Output

2. Parallel Wire Pairs

Two buried wires, relatively close spaced, in the center of the lane have also been used for lateral guidance. The magnetic field between the two wires, each carrying the same current in opposite directions, tends to be fairly uniform and is of the same polarity. These characteristics, tend to complicate the vehicle sensor.

The two wires which form a close-spaced loop have less self-inductance for a given length than the single wire which encloses a much larger area. Therefore, a longer length can be driven by a given generator. The lower inductance also allows higher frequencies to be used for signaling, speed control, or other communications.

The particular advantage of the two-wire system is brought about by transposing the wires at intervals as in Figure 13b. Both speed control and automatic positioning are then built into the design of the wire layout. Transposing the pair provides an alternating series of enclosed areas with opposite phases (instantaneous) of magnetism. A reference coil located to the rear of the lateral guidance sensor provides a reference from the signal phase of the area just being left which can be used to determine the phase of the area being entered. If the wires are transposed in the same pavement groove, the amplitude of the magnetic field will drop to near zero as the sensor passes over the transposition and this effect can be used to count area crossings. Position can be determined by keeping track of the number of crossings and the speed being maintained by reckoning the time elapsed between successive crossings.

As stated, the lateral deviation sensor is somewhat more complex than the single-wire sensor. While two amplitude comparing sensor coils can be used, two pairs of sensor coils will give better results by lessening the effect of ferrous masses near one of the wire pairs. Similarly, a phase-sensitive sensor, extending beyond the extent of the two wires as in Figure 13a, will yield a discriminator like curve as shown in Figure 12b. The averaging effect of using the signals from two separate wires here also tends to lessen the effect of magnetic field anomalies.

3. Buried Wire Pair (Radio Frequency)

This technique is very similar to the low frequency pair but the spacing of the wire pair is much closer. Frequencies on the order of 5 MHz have been proposed using 300-ohm twin lead such as that for television antenna lead for the wire pair. Significant radiation at the frequency is avoided with the less than a centimeter spacing.

The wire pair is treated as a single wire for lateral guidance. The sensors rely on amplitude comparison to detect deviation, but phase information derived from transposition is used for longitudinal reference. Sensors are ferrite loop antennas for both amplitude and phase data.

The higher frequency allows the guidance signal to be used as a carrier for substantial command and control data to be sent to the vehicle. Compared to the less than 10 kHz used in the other pair cited, a data rate 500 times higher can be used. This technique is not in use, however.

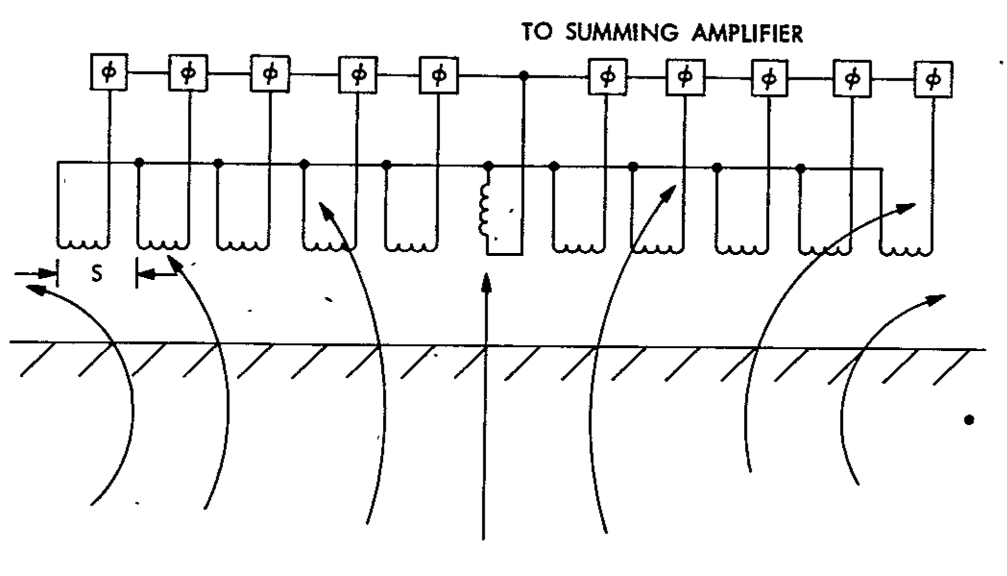

Figure 13a. Horizontal Component Detector for 2-Wire Pair

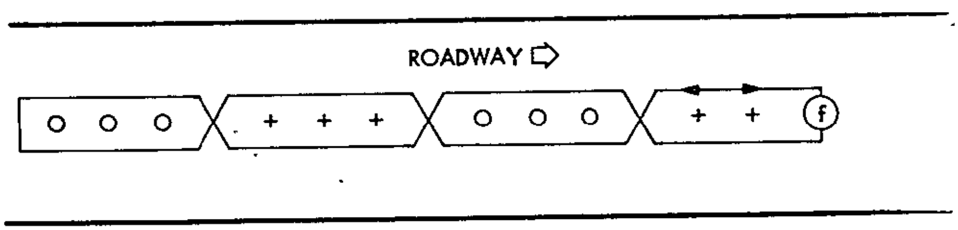

Figure 13b. Transposed Pair

4. Vehicle Excited Wires

A passive guidance technique that does not require wayside generators uses buried resonant loops. The loops are arrayed as single turn, narrow rectangles (Figure 14), spaced as with the wire pairs, placed end to end with adjacent loops. Tuning of the loops is accomplished with a series capacitor.

An oscillator on the vehicle, driving a coil beneath the vehicle, provides the excitation to the buried loops. The lateral guidance sensors are the same as those used in twin-wire systems. Similarly, the wires may be transposed for longitudinal reference.

This technique has some shortcomings. There is no communication link as in the foregoing methods. The exciting coil must be some distance from the sensor coils to allow them to function properly without being overloaded by a direct signal. This distance, if the loops are not overlapped, requires that the vehicle travel without guidance until both coil and sensors are over the same loop. This technique has only been proposed but never implemented.

5. Shaped Antennas

Buried antennas at very high, ultra high, or radar frequencies have been tried for vehicular communication and may provide guidance capabilities. The frequencies employed allow the antenna to vehicle spacing to be greater than a wavelength. The antennas are usually many wavelengths long.

The utility of these antennas is highly dependent on weather factors. Salt slush is a highly dissipative medium and causes severe attenuation. Similarly, a fraction of an inch of ice overlay will cause a diffraction of the radiated pattern which would affect the guidance function. The air water interface also causes high attenuation.

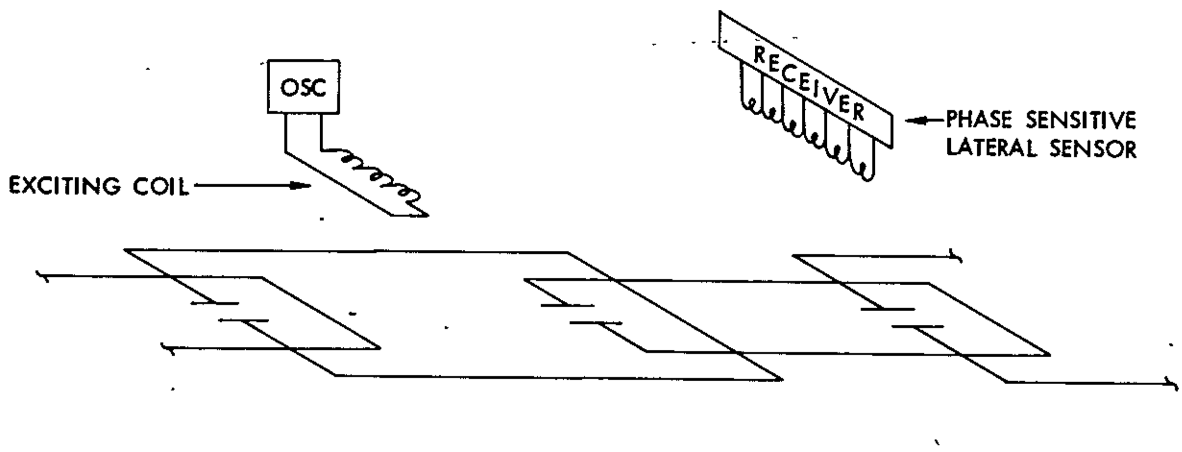

Figure 14. Vehicle Excited Loops

6. Magnetic "Nails"

A series of permanent magnets, driven into the roadway (Figure 15) along the center of the lane form the guides for this lateral control technique (Ref. 27). Two sensors, one each side of the row of magnets, are used to compare the amplitudes as the vehicle travels down the road. The relative amplitude comparison together with angular position data from the steering gear form three inputs to an on-board computer. As each "nail" is sensed, the deviation from equal amplitudes is used to calculate an average directional signal to the steering.

Two types of sensors may be used in this application: simple multiturn coils or magnetometers. The coils have the disadvantage that the peak signal amplitude is proportional to vehicle speed. The electronics required is relatively simpler than the magnetometer approach. The magnetometer, usually a second harmonic fluxgate, should maintain an output only dependent on the distance to the magnet and independent of speed but with more complex electronics.

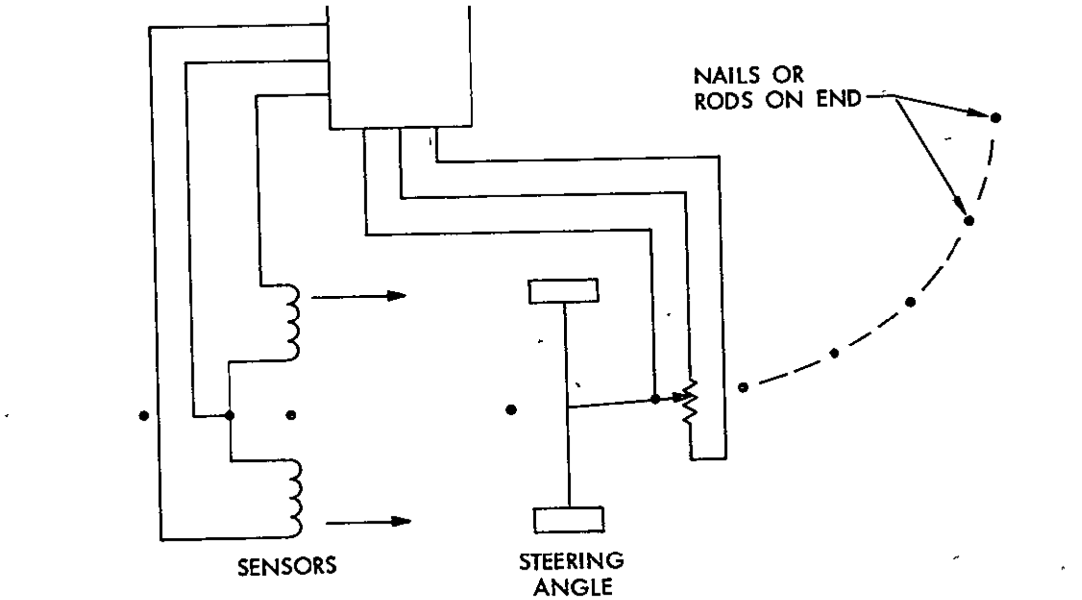

Figure 15. Magnetic Nails or Rods

7. Magnetic Rods

This is merely another implementation of the previous approach with the rod shaped permanent magnets lying buried in a groove along the roadway center line. The same type of sensors may be employed. The magnets may be laid head to tail (N pole to S pole) or in a periodically reversed pattern creating a code for longitudinal control. Similarly, reversals in the "nail" polarity can be used to form binary codes for longitudinal control. The rods may also be arrayed orthogonally to the direction of travel and polarity coded, but his would be a very inefficient installation because of the large number of transverse grooves required.

The magnets could also be in thin flat forms that are glued to the pavement surface. Both of these techniques have only been proposed.

8. Optical Reflectors

Plastic reflectors (Figure 16) similar to those now used as lane separators can form the reference line for lateral guidance. An illumination from beneath the vehicle would be directed at the reflectors. The reflected ray would be received by proportional or discrete sensors on the vehicle so that the lateral deviation could be detected or measured. The deviation together with the steering position would determine the direction and degree of correction to follow the reflector path.

This system would probably be very susceptible to weather conditions. Any residue of ice, snow, or water, or possibly dust might seriously degrade this approach.

9. Mechanical Grooves

A groove or slot in the roadway (Figure 17) could provide a lateral reference. The vehicle sensor would be a flexible "feeler" to detect lateral force as the vehicle deviates from the correct path.

The technique is fraught with drawbacks. The groove would have to be kept clear of residue of all types; perhaps by the vehicle feeler or an air blast from the vehicle. Wear would be another problem as the velocities involved probably mitigate against the use of small rollers on the feelers.

10. Mechanical Fin

This variation of the groove approach (Figure 18) is more practical. An elevated rubberoid or plastic, somewhat flexible, vertical fin can also supply the lateral reference. Feelers on the underside of the vehicle would be used to determine the relative position of the fin. The fin follower need only contact the fin at low speeds as an air cushion could be formed at higher speeds alleviating some wear problems. The fin is made flexible so that a vehicle may cross over it without rendering it useless.

Installation of the fin should not prove difficult. Weather effects may be adverse, particularly standing water and snow.

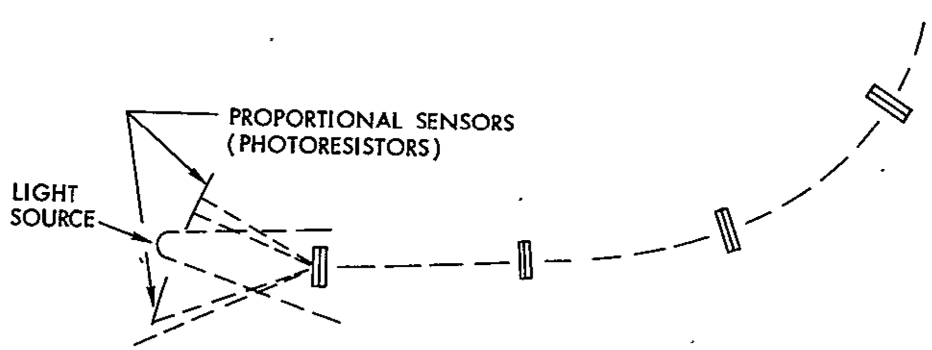

Figure 16. Optical Reflectors

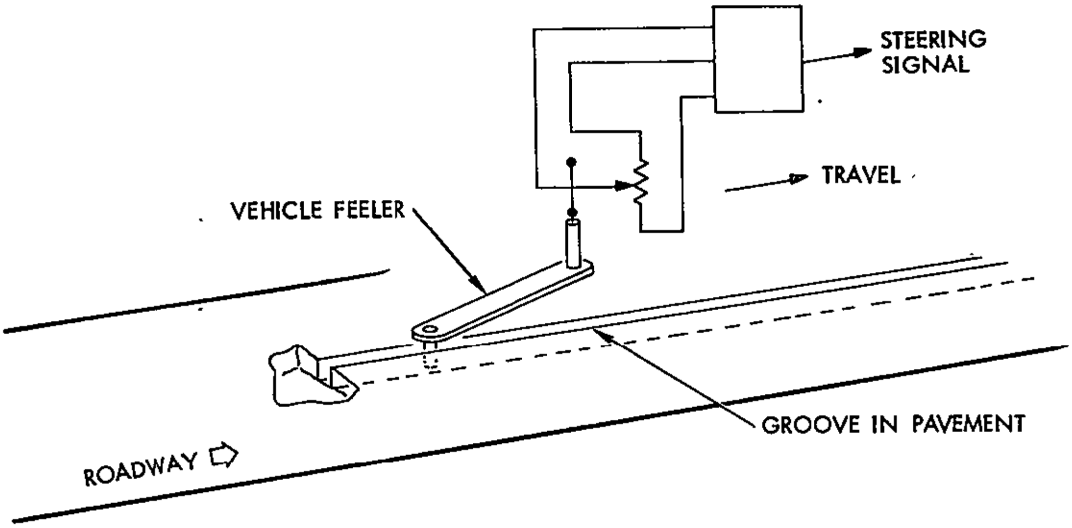

Figure 17. Mechanical Groove

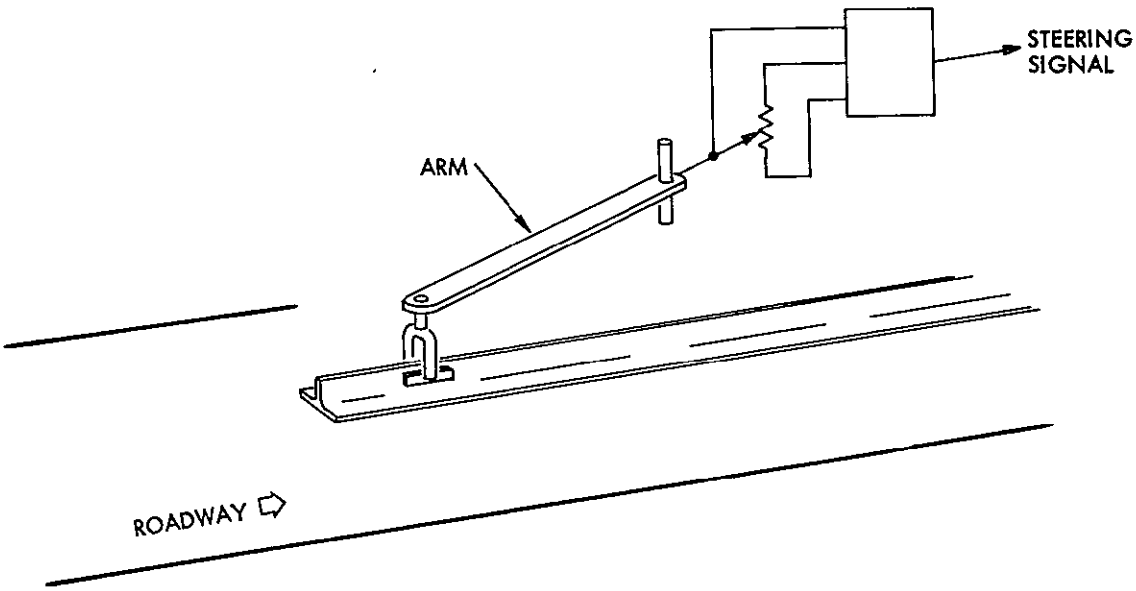

Figure 18. Mechanical Fin

11. Acoustic Discontinuity

A method recently proposed would employ a plastic pipe or tube buried in the center of the lane (Figure 19). This cylinder would be fluid filled to provide a medium with a greatly different sound transmission speed compared to either air or pavement. The discontinuity in sound speed and consequently reflectance of sonic energy would provide the lateral reference data. The means to accomplish this (that is, the sensor design) has not been established. How well this technique would work with residual rain, snow, or ice has also not been determined.

C. LONGITUDINAL GUIDANCE

The control of the vehicle's motion along the roadway may be controlled by commands in concert with measurements made to the roadway or leading vehicles. This section concerns the methods of making the roadway measurements. Both distributed means and discrete fiducial references are discussed.

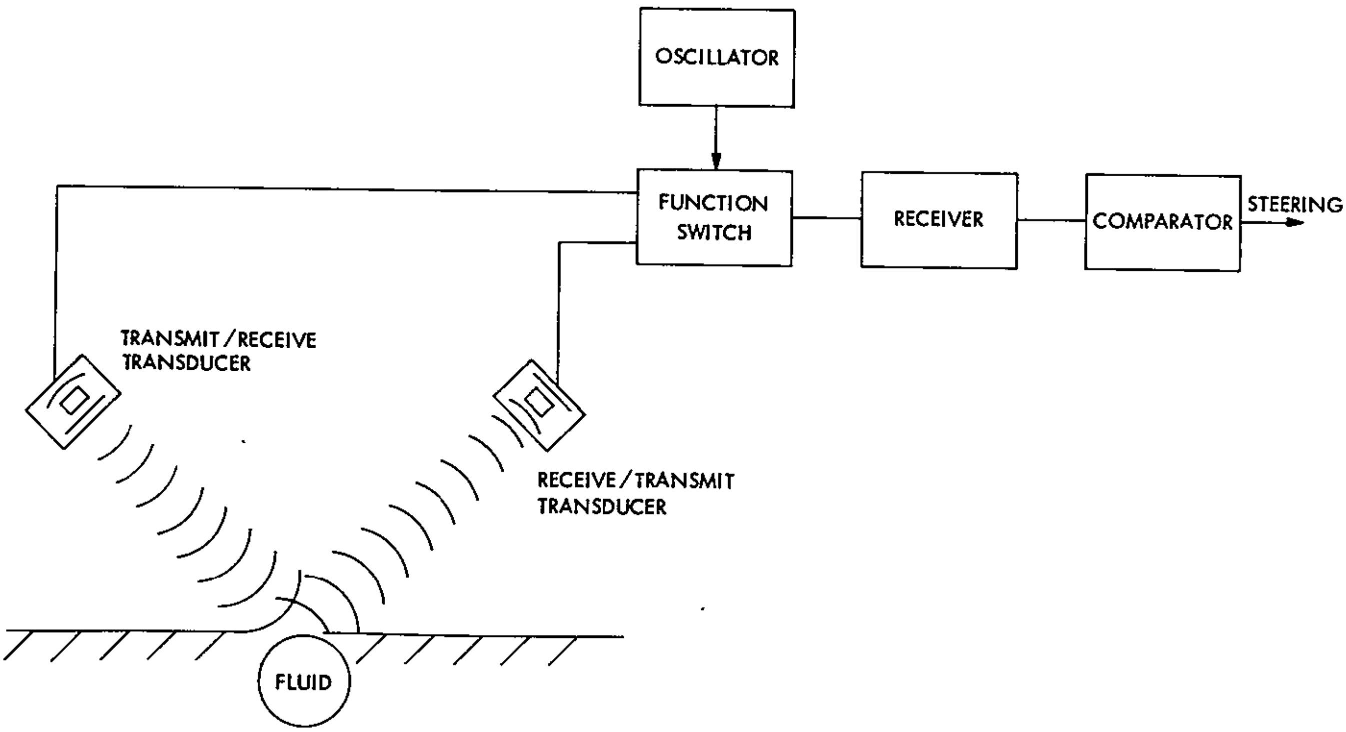

Figure 19. Acoustic Discontinuity

1. Two Frequency Method

This technique requires two nearly parallel wires (Figure 20a)--one excited at a frequency, f, and the other excited at the opposite end by a frequency, f + Δf (Ref. 28). A point where the relative phase of the two signals is constant tends to move toward the source of the lower frequency (Figure 20b). The velocity of such a point is CΔf/2f where C is the velocity of propagation along the wires. The spacing between points of the same phase difference is regular and inversely related to the phase velocity.

The constant velocity longitudinal reference established by the two frequencies is measured aboard the vehicle by an electronic phasemeter. The signal from the phasemeter is used in the speed control loop.

The frequencies required seem to be fairly high as the fraction Δf/2f multiplies the speed of light to achieve the value for the vehicle velocity. A speed of 30 mph (48.3 km/hr) requires the fraction to be about $1/(22 \times 10^6)$ or a Δf of 1 Hz between two frequencies of 11 mHz. State-of-the-art technology can reliably reduce each of the frequencies by a thousand or more bringing the carriers into the frequency domain used for lateral guidance, thereby combining both guidance functions into one wire.

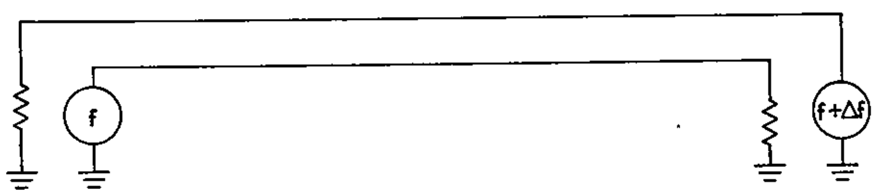

Figure 20a. Two Frequency Wire Pair

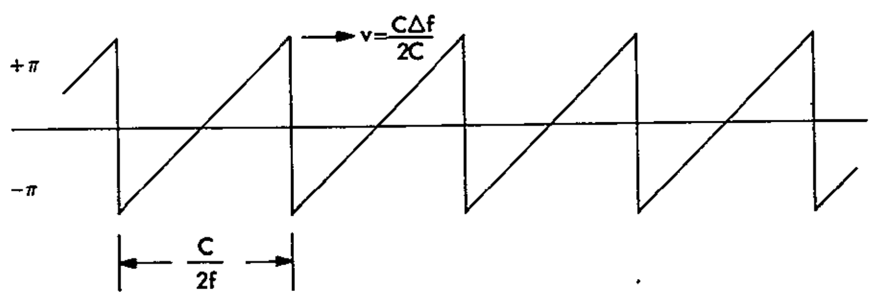

Figure 20b. Phase Pattern

2. Helically Wound Wire Pair

An improvement over the prior method utilizes cables wound from two wire pairs (Ref. 29). These cables are wound with a constant pitch of one foot or so (Figure 21a). When two of these cables are arrayed in parallel (Figure 21b) along the roadway and excited properly, a stationary phase pattern is produced. The excitation to the pairs in each cable differs by 90 electrical degrees and is typically near 10 kHz which is suitable for lateral guidance. The one-foot pitch in each cable results in a phase pattern that repeats every six inches. The electrical pitch that can be realized is the reciprocal of the sum of the reciprocals of each of the cable pitches. It can, therefore, be no greater than the tighter wound cable.

A vehicle traveling along the cables and equipped with a phasemeter to compare the signals from the two cables can count phase repetitions to determine position. The horizontal component of the signals from each cable is sensed with a multiturn coil as in lateral guidance methods. It was determined experimentally that both cables having the same "hand" pitch direction resulted in some coupling between lateral and longitudinal motions of the sensors. By reversing the pitch direction of one of the cables, there appeared to be a first-order cancellation of the coupling effect.

If, as in the previous method, the two cables are energized with slightly differing frequencies, the phase pattern can be made to move with a desired velocity and direction. The velocity is twice the frequency difference divided by the electrical pitch. A one hertz difference results in a two-foot-per-second velocity.

The ratio of frequency difference to carrier frequency is not a function of the propagation velocity in this method. While the prior technique is realizable, this technique has three advantages. First, both generators can be located at the same end of the wire; second, the velocity is a function of controllable cable parameters; and third, the spacing between similar phase locations is not a function of frequency.

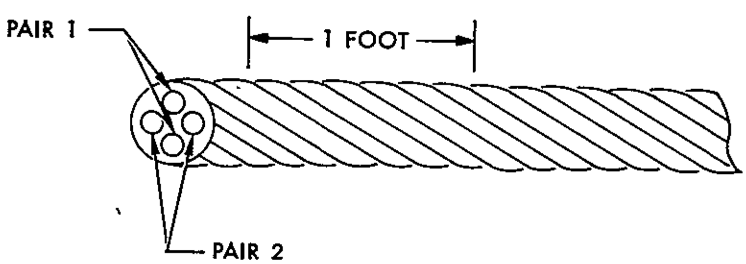

Figure 21a. Helical Wire

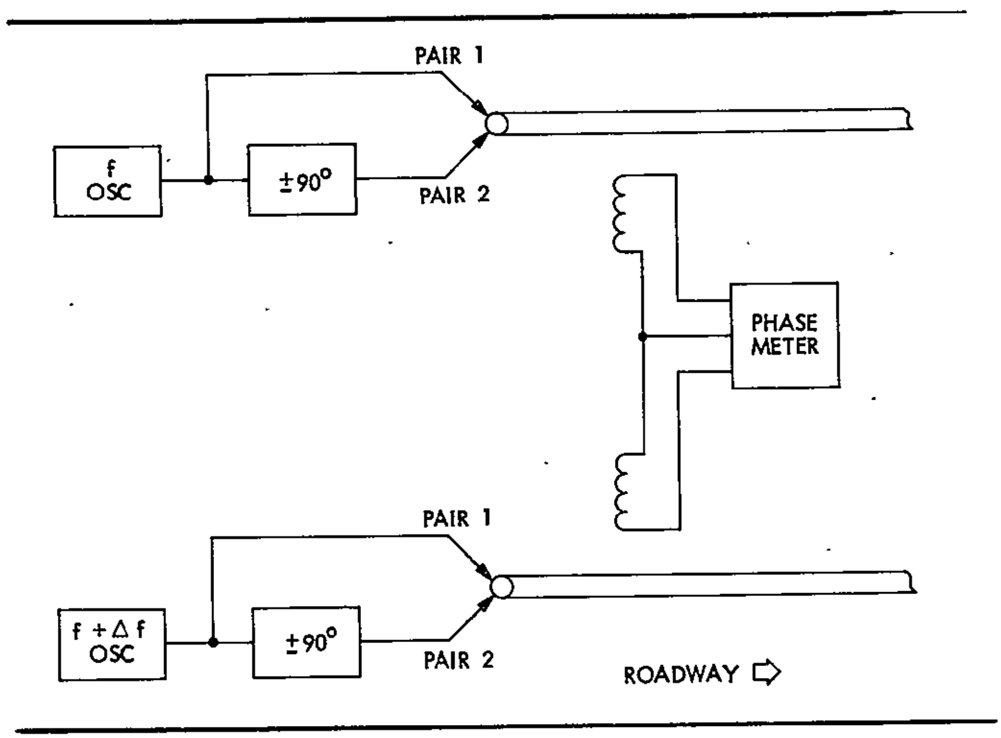

Figure 21b. Two Wire Pair

3. Transposed Wires

The utility of a wire pair periodically transposed as a position determining means was discussed in the lateral guidance section. The transpositions become fiducial marks and are obviously fixed at installation.

4. Single Wire With Shaped Return

This technique is more commonly used on rail transit where the wires can be disposed between the rails and not buried. A long wire loop is laid between the tracks - primarily for communication to the vehicle by inductive means. The return wire of the loop is laid in a serpentine, triangular, or square serrated pattern. This allows an additional sensing coil beneath the vehicle to be alternately in and out of the loop boundaries as the vehicle progresses. These transitions can then be counted for positioning and velocity control.

The technique might be adapted for nontracked vehicle use, but the burying of the shaped return wire would be difficult. The number of separate pavement cuts required would make this technique difficult to justify when compared with transposed wires.

D. FIDUCIAL INDEXES

Discrete markers or reference points can be established for positioning and velocity measurement or control. The markers are either active or passive.

1. Passive Markers

a. Metallic Plates. Small plates may be buried beneath or affixed to the pavement at intervals. The presence of these plates is detected by metal detection or magnetic sensors on the vehicle and the number of detections accumulated.

b. Rod Magnets. Vertical or horizontal magnets placed in the pavement can and are being used for fiducial data. In one application the magnets are arranged in coded sequences by having either the N or S pole topmost in a series of magnets. These then form a code for a particular location or distance from a previous location. The detector for this type of system is either a coil or magnetometer to detect the field and the polarity.

c. Dipoles. Burying short wire rods cut to predetermined lengths allows the detection of the reference by radar means. If the wires are cut to one-half wavelength at the frequency employed, substantial energy is reradiated when they are illuminated by the radar.

The sensor required on the vehicle entails a CW or pulsed very low power radar and receiver to detect the reradiated energy. The detections are counted or used for speed control.

A variation of the dipole method uses wires with a semiconductor diode in the center of two wires. These form parametric reflectors which radiate energy at twice the frequency of the illuminating energy. This tends to simplify the receiver design as the effect of direct radiation has been eliminated.

2. Active Markers

a. Magnetometers. Magnetometers buried in the roadway are used for detecting automobiles, guideway transit vehicles, and trains. The magnetometer is essentially a presence detector which notes the passage of a vehicle and the duration of time that the vehicle is over it.

The magnetometer data is usually used in wayside traffic counting and measuring applications. It could also be used as the measuring device for issuing speed controlling commands.

b. Loop Detectors. The loop detector is a large, buried, few-turn coil which detects the presence of vehicles by the change in inductance. The application and use has been primarily the same as the magnetometer detector and could be used in speed controlling.

The loop does have the additional capability of being the antenna of a communication system. This has been exploited in train and nontransit systems. Both the communication and detection processes can be used simultaneously.

c. Buried Radar Antennas. The antennas used for broadband communication with vehicles from beneath the roadway might also be used as presence detectors by reflected energy detection. The effects of weather residuals would need to be studied for this use.

E. AUTOMOTIVE ELEMENTS

1. Lateral Sensors

The lateral sensors for almost all of the techniques provide an output which is proportional to the amount of lateral deviation from the desired path. The proportional output may not be linear but in most instances is monotonic over the expected lateral motion that should occur. The lateral motion limit is usually reached when one of the sensors in the pair is above the desired lateral path centerline or the output has reached a maximum value. Behavior of the sensor output beyond this limit is usually disregarded and guidance there is determined by the technique used for path acquisition.

The magnetic field amplitude sensors, magnetic coils, or magnetometers, as well as the radio frequency amplitude sensors, are positioned beneath the vehicle in close proximity to the roadway. The spacing between the sensors usually determines the extent of lateral motion possible. Similarly, the length of the phase sensitive magnetic array determines the amount of lateral motion possible.

2. Signal Conditioning

The ac signals from the sensors usually have to be amplified before processing. Vertical vehicular motions or other effects which cause common changes will affect the magnitude of most comparison voltages. Long-term or short-time changes in amplifier gain will cause spurious comparison voltages to be developed.

For these reasons, automatic gain control (AGC) and gain stability are both required. The time constant of the automatic gain must be such that the lateral motions to be detected are not disguised. One method derives the AGC from the sum of the two signals and applies the control equally to both amplifiers. Long-term and short-term gain stability can be assured by utilizing operational amplifier techniques where the gain is determined by stable passive components and not the active gain stages.

The sensors intended to derive phase data avoid most of the foregoing problems. The only requirements are that the gain bandwidth product of the amplifiers be adequate under minimum amplitude input and that phase distortion be avoided.

3. Processing

The comparison of the amplitude signals is accomplished by rectification (usually of opposite polarities) of the two signals. The resulting dc voltages are then summed in an operational amplifier to develop the lateral error voltage for steering. Analog-to-digital conversion of the rectified voltages for subsequent digital processing is also possible. Similarly, voltage-to-frequency conversion and subsequent frequency comparison may also be used.

The phase comparison is accomplished primarily with digital logic devices which can function as phasemeters, such as the exclusive-OR or the edge triggered flip-flop. The output of either of these devices is then filtered to develop the dc steering voltage.

The phase detector technique which uses a multiplicity of coils and phase detectors develops a steering signal proportional to offset, but in a series of steps. To avoid the effect of the step discontinuities, the signal is integrated before being used for steering control.

4. Steering

The three most common steering mechanisms for passenger cars are the recirculating ball nut, worm and sector, and rack and pinion. Servos employed to drive these steering gears are electric and electric controlled hydraulic (Ref. 30). Positional feedback, usually potentiometer controlled dc voltage, is common. Most attempts to automate the steering at the front wheels have had to provide a means of declutching the steering wheel. The steering wheel inertia load is substantial and is greatly magnified in effect by the steering gear ratio. Owing to the large forces and relatively short motions involved, hydraulic linear actuators are used, as is common in manually controlled power steering. The actuator drives the linkage connecting the front wheels.

Electric servomotors with worm and pinion gearing are sometimes used where the steering shaft and wheel are driven directly. This implementation also requires that the electric motor be declutched or the worm be disengaged from the pinion gear to avoid inertia effects when the steering wheel is manually operated.

The servos to operate either of the power mechanisms are usually second-order devices to achieve zero position error. Rate input is required and is normally a derived signal obtained by differentiation of the control signal from the sensor signal conditioner.

F. SPEED CONTROL

Continuous speed control is often determined by a modulation signal superimposed on the lateral guidance carrier or by tone or digital commands. Some continuous measurement of the vehicular velocity is required in addition to the positional data provided by the longitudinal guidance references, particularly with the widely spaced positional reference methods. The phase meter or point follower system has continuous speed control as a technique function and does not require other measurements. Figure 22 is an overall block diagram of speed and position control functions.

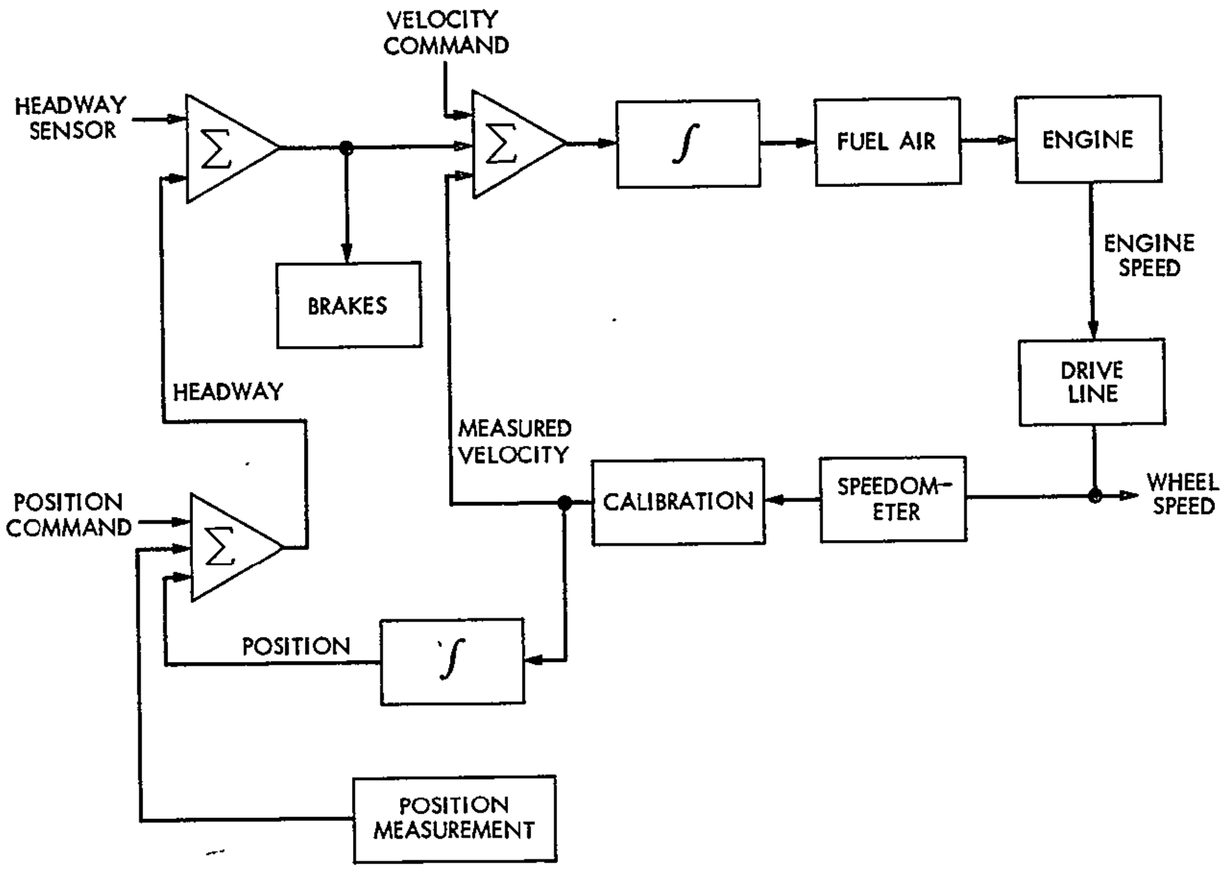

Figure 22. Speed Control Block Diagram

1. Sensors

A speedometer cable driven dc generator or drive line driven toothed wheel and proximity coil are the two most common velocity measuring devices providing electrical signals (Refs. 31 and 32). The first yields a voltage and the second a frequency proportional to speed. These devices provide a speed measurement which has intrinsic errors due to tire wear, inflation pressure changes, and wheel slip. The positional data available from the longitudinal sensors can be used to provide correctional data.

Continuous speed sensors which can measure true ground speed have been developed in three implementations. There are acoustic, radar, and laser mechanizations which provide a noncontact measure of the velocity of the roadway beneath the vehicle. The acoustic and radar methods which have been produced in prototype or production versions rely on the doppler shift of the reflected energy which increases with increasing speed. The radar and acoustic devices are usually operated in a continuous wave mode and the illuminating energy directed forward toward the road at a downward angle. The reflected energy is compared with the radiated, and the beat frequency difference which is the measure of speed is extracted.

The laser device provides a laser beam directed vertically downward toward the road surface. This device has been demonstrated as part of a vehicle locator system (Ref. 2) and is also used as a non-contact speed detector in steel rolling mills. The reflected "spot" contains a speckle pattern which moves with a velocity twice that of the reflecting surface. The forward component of the speckle pattern is extracted with a transverse diffraction grating and a light sensitive detector. A phase locked loop or synchronous amplifier is then used to extract and track a frequency which is determined solely by the motion over the road and the spacing in the grating. The frequency is a direct indication of speed.

2. Signal Conditioning

The dc generator speed sensor provides a voltage which can be used without further modification. Some implementations might use a voltage-to-frequency conversion or analog-to-digital conversion for computer input.

The toothed wheel provides a variable frequency signal which must be amplified to be used. A tracking phase locked loop is normally used to eliminate amplitude variations and the ability to apply corrections to the frequency based on the positional signals.

The radar, acoustic, and laser instruments also provide frequencies proportional to speed which generally need no further conditioning.

3. Processing

Speed control by positional data points and commands, either stored on-board or sent to the vehicle requires some method to measure the elapsed time between reference points. The speed command might be the value of the time required to cover the distance between reference points. In this case a comparison of the command time value and measured elapsed time made at each reference indicates whether the vehicle should speed up or slow down. The vehicle operates in an open-loop mode between corrections. A speedometer control allows closed loop operation to be maintained by continuous adjustment of the speed in accord with the commanded value and previous correction.

Tone type speed control signals allow direct and continuous comparison with those vehicle speedometers which yield a frequency output. The true ground speed devices need no calibration correction signals, but those operating through the vehicle wheels do because of slip.

The speed commands may be times or tones but may also be the actual speed, or a code representing the speed, or an acceleration profile. The variations are many and the implementations with discrete logic elements can have very different topologies. The obvious differences tend to disappear when microprocessor implementation is used. The differences then show up in the software or program.

The processing for point follower speed control is merely a continuous closed loop system. Additional processing may be required if corrective actions are to be taken in the event the vehicle slips from one point to the next or advances due to overspeed. The action to be taken depends upon the entire system design, including such factors as nominal speed, headway, braking ability, and headway sensing.

G. HEADWAY SENSORS

Devices to determine if a safe distance exists ahead of a vehicle are somewhat akin to the traveling block system used by guided transit. If a certain distance ahead is clear, then maximum speed may be maintained. If an object is detected but still at some distance, then a moderate or reduced speed is to be observed. When the distance falls to some minimum, the following vehicle is obliged to stop.

Some transit systems have proposed headway sensors as the speed controlling device (Ref. 33). In automotive service, the prime emphasis has been to develop headway sensors for collision avoidance or air bag deployment.

Headway sensors have been primarily radar based using continuous wave, ultra short pulse, or sweep frequency (as in a radar altimeter). Some techniques have required cooperating reflectors on the rear of the preceding vehicle while others use parametric passive antennas as frequency doublers on the car ahead. Roadside clutter and opposing traffic have posed serious obstacles to the development of viable devices. Acoustic and laser techniques have and are being investigated, but they also have similar problems.

The headway sensor output is used as an overriding command to the speed control circuitry. The headway sensor is considered a vital function to vehicular safety.

A telemetry approach to headway sensing has been proposed whereby each vehicle transmits its position and speed to the vehicle nearby (Ref. 33). This technique also transmits acceleration data. Each vehicle has a signal processor and becomes a part of a distributed computer guidance system.

H. ACTUATORS

Brake and throttle actuators which can perform under automatic control and not interfere with manual operation are needed for automotive application. Throttle actuators are available with limited speed control range. These criteria are usually met with pneumatic devices where engine manifold and the atmosphere provide the operating forces. Hydraulic actuators are also used but they are more difficult to decouple for manual operating conditions.

Position feedback is sometimes required from the actuators to the speed control servo. Potentiometers are commonly used in developmental systems, but these may be replaced with capacitive-position-to-frequency sensors currently being developed.

I. GUIDANCE-BASED TESTING

The lateral and longitudinal guidance elements interface in three functional areas on the automobile - steering, braking, and air-fuel metering. The headway sensor system independently interfaces with the braking system and may also have fuel and ignition cut-off capabilities.

The automation required to perform lateral guidance can provide the means to measure the total free play in steering. This free play is made up of looseness in steering arm and relay rod ends and the backlash in the steering gear box or rack and pinion assembly. The arm and rod ends are involved regardless of the type of steering mechanization or the automatic guidance servo. Position sensors to provide measures of the angular motion of each wheel together with the motion of the servo will determine the deadband in the arm and rod ends. These sensors may also be used to measure toe-in and steering geometry (not camber or caster). If the servo is above the steering gear, then the backlash is also included in the deadband, and a third position sensor will be necessary to apportion the looseness to the contributing elements.

There are and have been several original equipment and after market devices installed to help maintain constant vehicle speed. These devices use the revolutions of the speedometer cable as the speed reference and the servo typically uses manifold depression to provide a means of independently controlling throttle valve position. The servo is usually analog at present, but speed control is a prime candidate for microprocessor control.

Current speed controls can provide a starting point for longitudinal control interfacing and also a means of determining some dynamic engine vehicle performance tests. The tests would probably be associated with step-wise speed increases of various amounts to determine if the accelerations indicate sufficient engine reserve for automatic operation. Detailed diagnosis for lack of engine reserve must rely on additional tests.

The longitudinal guidance system as well as the headway sensor must also interface with the braking system. In a similar manner to accelerations, overall braking system performance checks could be made by commanded step-wise speed reductions. Again, more detailed measurements which are independent of the actuation means (i.e., automatic or manual) would be needed to determine pad or lining wear, brake line pressures, leak rate, fluid level, or any other factor which would be critical to braking performance.

SECTION III

PERFORMANCE CRITERIA

A. INTRODUCTION

This section of the report is concerned with determining which vehicle performance parameters should be measured and what indications should be provided for the purpose of meeting highway entry criteria. A qualitative assessment of these criteria is presented.

The contributors to mechanically caused accidents as well as parts expected to be replaced during extended vehicle life are presented and related. A discussion of nonaccident breakdowns and probable causes is included.

The last part outlines several possible configurations of on-board safety-telemetry processing equipment in relation to other vehicular electronic subsystems.

B. HIGHWAY ENTRY CRITERIA

The entry criteria for automated interurban highways must screen out incompletely equipped, improperly performing, and potentially unreliable vehicles. These vehicles, if allowed entry, might break down either suddenly or gradually becoming a hazard to other vehicles.

The incompletely equipped vehicle is probably the easiest to detect but might prove the most difficult to deter. The improperly performing vehicle can be detected with more difficulty but with a high degree of certainty. The properly operating but potentially unreliable vehicle is obviously the most difficult to detect with surety.

Sufficient fuel to complete the journey is the foremost requirement for entry. The other very broad requirement is that adequate performance can be maintained throughout the journey. The performance dynamic criteria are in the steering, braking, acceleration, speed control, and economy areas.

1. Dynamic Performance

The steering must have adequate responsiveness with proper damping and limited overshoot. The tracking offset, if any, must be limited to a very small amount of the tracking range of the lateral guidance sensor.

Braking effectiveness criteria should cover the deceleration capabilities in both normal speed control functions and emergency situations. The criteria might relate the pressure on the pedal or in the braking system to the deceleration achieved.

The acceleration performance must be such as to meet the longitudinal control requirements at grade changes and merges (if any). Both part and full throttle acceleration criteria are required. The former is primarily for speed control while the latter is needed to measure engine and transmission conditions and possibly allow for emergency maneuvers; if such are to be allowed in the guidance system design.

Criteria for speed control must determine if the speed control tolerance is within the accuracy required for the method employed. Completely deterministic speed control systems, where the vehicle follows an imaginary point, need as criteria the data on vehicle displacement from the desired position. This longitudinal error is related to the "tightness" of the speed control loop. On open loop or commanded speed control, the accuracy requirement is more stringent because vehicles must be prevented from bunching to the point where the on-board headway sensors take over and modify the distance to the car ahead. This would change the operation of the guidance system to a different mode. Surging, which might be a result of a poorly-tuned engine or a faulty on-board speed control system, should also be included in the speed control measurement criteria.

The economy or miles per gallon currently being achieved is another dynamic entry criteria. This is naturally related to the fuel on board and the length of the journey and would establish that the trip can or cannot be completed with sufficient fuel margin.

The last dynamic performance criteria is related to the on-board headway sensor. The rate of closure sensitivity as well as the minimum distance threshold must be determined to determine if air bag (or other restraint) actuation or braking may be properly performed.

2. Static Performance

Static performance criteria which do not require vehicle motion or the effect of vehicle dynamics must also be met. The principal measure that must be made is the weight of the vehicle which is required to determine expected vehicle dynamics. Other examples of static criteria would be the determination of the braking actuator response to the braking signal. The actual criteria would depend on whether the braking system is proportional or not. A similar criteria would be applied to the throttle control portion of the speed control system. The steering control actuation in response to a steering signal is another example of static criteria. Most automatic steering systems would disconnect the manual steering wheel to reduce the inertial loading on the steering servo. Whether this has been accomplished or not is another static criteria. The minimum actuation distance for the anticollision or air bag headway sensor is a static criteria which may be measured along with the dynamic rate of closure criteria.

3. Indications

Highway entry criteria should also be concerned with the age and prior service of original and replaced parts. Replaced parts include those replaced at normal maintenance intervals (such as spark plugs), those substituted for failed parts (e.g., belts and hoses), or parts near end of life (brakes, shock absorbers, etc.). Service intervals currently promulgated by automobile and parts manufacturers are usually defined in terms of elapsed time or mileage for most maintenance. Engine oil and various filter replacement intervals are about the only ones that are recognized to be affected by other conditions such as sustained high speed, stop-and-go driving, or dusty conditions.

Additional indications which might be judged as criteria are measures of tire tread depth or brake lining thickness at the last several inspections. These data would indicate the rate of wear and possibly provide end of life prediction data. In a similar manner, the economy history of the vehicle could indicate a deteriorating engine condition.

4. Sensed Parameters

The primary parameters that should be sensed to determine if a vehicle meets entry criteria are at least those now provided to the manual operator. These are not limited to those parameters which are displayed by instruments on the dash but also include fluid levels which can be measured by dipstick or visual sighting. Also included are those equipments which can be judged by observing the operation or physical condition such as lights, windshield wipers, tires, glass heater-defroster, door and hood latches, etc.

5. Failures and Replacements

Mechanical failures are the principal cause of accidents in only a small percentage of single and multiple car mishaps. An ordered list has been determined (Ref. 34) and is essentially as follows:

(1) Brake performance.

(2) Vehicle driveability (engine performance).

(3) Suspension.

(4) Brake lines and wheel cylinders.

(5) Drums and discs.

(6) Accelerator linkage.

(7) Power steering.

(8) Wheel balance and alignment.

(9) Hood latch.

(10) Defroster.

(11) Headlights.

(12) Windshield wipers.

(13) Automatic transmission.

Another study (Ref. 35) estimated which parts on a 1970 standard sized automobile would probably need replacement before 100,000 odometer indicated miles had been accumulated. This list, not ordered as to priority, is as follows:

(1) Battery and cables.

(2) Radiator hoses.

(3) Alternator.

(4) Belts.

(5) Water pump.

(6) Distributor cap, points, condensor, rotor.

(7) Heater hoses.

(8) Air filter(s).

(9) PCV valve.

(10) Ignition coil.

(11) Air pump.

(12) Timing gear chain.

(13) Fuel vapor canister filter.

(14) Fuel pump.

(15) Oil filter.

(16) Control arm bushing (steering).

(17) Spark plugs.

(18) Spark plug wires.

(19) Exhaust pipe.

(20) Voltage regulator.

(21) Windshield wiper blades.

(22) Crossover pipe (exhaust).

(23) Shock absorbers.

(24) Tie rod ends.

(25) Brake pads, disc parts, linings, wheel cylinder parts.

(26) Ball joints.

(27) Master cylinder.

(28) Universal joints.

(29) Starter.

(30) Brake rotors or discs.

(31) Tires.

(32) Muffler.

(33) Tail pipe.

(34) Steering idler arm.

The engine, transmission, and differential were expected to last the entire 100,000 miles.

The wear-out list appears very lengthy because many items which are to be routinely replaced at prescribed intervals are included. There are also many items which are often replaced on the basis of age rather than mileage. Also included are many items where replacement could be avoided through a proper maintenance regime. The list is very inclusive but might be characterized as pessimistic.

The first five items on the list of accident contributors indicate that maintaining the dynamic performance of the braking and engine systems would help in avoiding mechanically induced accidents. The suspension category includes tie rod ends, ball joints, and to a lesser degree shock absorbers. These suspension components more likely contribute to accidents through catastrophic failure rather than gradual degradation. The gradual wear would probably lead to a lack of mechanical integrity failure if maintenance were not performed and this wear would certainly cause difficulty in the servo loop of an automatic guidance system. Wear indicators exist for ball joints which rely on manual inspection (sight or feel of a pin projection) but no wear indicator was found for tie rod ends in the course of the study.

6. Breakdowns

Vehicle breakdowns, where the vehicle is forced to a stop within a short time after a malfunction, are commonly caused by the following (arranged approximately in decreasing order of likelihood):

(1) Out of gas.

(2) Tire failure - blowout or flat.

(3) Overheating - belt breakage, coolant loss, lack of oil, vapor lock.

(4) Ignition - primary circuit failure.

(5) Driveline, engine, transmission.

(6) Speed control - throttle and brake actuators.

(7) Lateral control - hydraulic pump belt.

Items (6) and (7) are assumed for automatic highway application.

The out-of-gas situation is seldom caused by equipment failure or malfunction. The usual reason is inattention to a low fuel indication. The measurement technology is well established.

Tire failures, particularly flats caused by punctures, are much more likely with tires that are bald or with little tread. Blowouts or sidewall failures are often the result of overheating due to underflation, prior injury (rocks or curbs), or occasionally manufacturing faults. At present, it appears that only tire pressure will be a feasible continuous measure. Tread wear and obvious injuries may be determined during inspections while internal faults are only detectable by sophisticated testers such as that developed by Southwest Research Institute.

Overheating may be the result of any of many failures. Fan belt failure is a common cause primarily because the water pump is driven from the same shaft. The fan is not usually needed at highway speeds but water circulation is essential. Other failures, usually heater or radiator hose breakage, result in a dramatic coolant loss and overheating. This loss sometimes goes undetected by the temperature gauge as the sensor relies on the heat transfer from fluid to properly indicate high temperature and steam or vapor does not supply sufficient heat. Lack of oil is another cause of overheating, but, like lack of fuel, is usually caused by lack of attention. It is very seldom that an on-road vehicle suffers a sudden loss of oil through a loss of integrity of the oil system. Even an oil pump failure will indicate through loss of pressure well before overheating occurs. High underhood temperatures, occurring due to several conditions such as grades, following winds, air temperature, air conditioner use, and improper spark timing can cause vapor lock when the fuel boils (usually in an unpressurized or suction line). Vapor lock will result in a breakdown which can be misinterpreted as an out of gas condition, which is technically true.

Ignition failures in the primary circuit which cause a total loss of spark plug voltage are another breakdown cause. In Kettering ignition, this failure is usually due to lack of maintenance of the points and occurs when the cam rubbing block is worn to an extent that the points will not open. This is easily discerned from a dwell angle measurement. Capacitor failure is another cause of loss of spark as is an open coil. Either of these failures are rare and usually are a result of manufacturing errors, particularly if the fault occurs shortly after installation. Coils can be damaged by abuse by forcing internal secondary circuit arcing which can happen if the engine is cranked with the high tension lead dangling in air. Other primary circuit failures are usually the result of open connections.

The high energy or breakerless ignitions which rely heavily on semiconductor technology and are surplanting the point systems are subject to failures of a different sort. Underhood heat, moisture, vibration, and impurities occurring during manufacture are some of the failure causes. The first three can be minimized by component placement and the last by improved quality control. Improper application or exposure of semiconductors to high-energy voltage transients are also causes of failure which can be avoided by proper engineering and attention to the environment.

The driveline, engine, or transmission as the principal cause of a breakdown is becoming more and more unlikely. The improvement in reliability of these major components has been steadily improving and will no doubt continue.

The last two causes of breakdown are conjectures and are placed at the bottom of the list to indicate that they must be equal or superior to the propulsion system in reliability for automatic highways. The speed control, particularly the throttle and brake actuators, must be extremely reliable, especially in situations where there is little headway between vehicles. While the speed control system is probably backed up by an on-board headway sensor, a failure in either throttle or braking could slow or stop all following vehicles. An overspeed condition might result in the headway sensor applying the brakes to avoid closure with the car ahead while the throttle is being opened by the fault.

The lateral guidance steering system should be the most reliable subsystem as a failure at high speed could quickly become catastrophic. A fail safe system is required and any single failure shoud not render the system inoperative. The manual operator cannot be depended upon to provide the back-up function. Redundancy in sensors and electronics is probably called for as well as means to back up mechanical linkage connections to avoid complete loss of function. An example of the latter might be an auxiliary connection around a tie rod end which would come into use if the tie rod end came apart. Other steering and suspension parts are also candidates for fail safe treatment.

7. Summary

The entry criteria that vehicles would have to meet to enter automatic highways are, in the main, the same that a cautious driver would require of a vehicle before embarking on a similar trip. These are primarily static measurements or conditions with well established limits of wear, component age, accrued mileage, and quantities of fuel, oil, water, and other liquids and lubricants.

The dynamic performance which would be demanded by automatic highways can only be qualitatively judged at this time. That is, numerical values of acceleration and deceleration or lateral stability cannot be assigned. These are functions of vehicle size, weight, propulsion means, and suspension. They can be determined by simulation (Ref. 36) or by experiment (Ref. 37), but a parametric study at this time is probably premature.

C. PRECISION OF MEASUREMENTS

Engine performance parameters which affect driveability, performance and economy are well understood by the industry as to the range and precision of measurement required. The accuracies that must be maintained during the life of the sensor and under the environments experienced are also well established. Fluid levels to be maintained and the low (or high) limits that can be tolerated for extended periods are also well known.

The fuel, the most rapidly consumed item, dictates the remaining range of the vehicle. The measure of fuel quantity depends on the economy of the vehicle and the trip duration and profile. The length and topography of automated highways will be different, requiring different quantities of fuel as a minimum for completion. Fuel stops on automated highways are not contemplated.

Since it is better to be cautious and avoid running out of gas, the present philosophy of fuel measurement should be maintained. That is, when "it" reads empty, there are a couple of gallons left. For automated highway use, the fuel level sensor should probably read to the nearest gallon which is 4% to 10% of a full tank and should have a tolerance that favors a conservative measurement.

Measurements of the tire treads and brake linings should also be on the careful side. The tire tread depth is probably a good indicator of remaining life particularly if uniform across the width of the tire. This wear pattern indicates a proper inflation history, mechanical alignment and freedom from some forms of driving abuse. The tire tread wear versus mileage at uniform speeds such as on an automated highway and at different loads has probably been investigated at length, and the mandated tread wear indicators provide a universally accepted minimum tread depth. Therefore, it appears that the tire should be measured precisely enough to assure that this minimum depth will not be reached at the end of the journey.

If a 20,000 mile tire with an initial tread of 5/16 in. is allowed to wear to 1/8 in., then the wear rate is roughly .01 in. per thousand miles. Braced tread tires achieve wear rates of less than half that value. Manually operated tread depth gauges measure to 1/32 in.

(about .03 in.). It appears that a measurement precision in the range of .01 to .03 would be adequate.

The precision of brake lining measurements is very difficult to predict, particularly if one supposes that a well designed automated highway should only require one brake application when slowing down to leave. If more braking applications are required and emergency stops must be considered, then lining thickness adequate for the stops must be provided. Current on-board brake inspection systems vary widely in performance and effectiveness (Ref. 38) but all provide warnings well in advance of complete wearout. The measurement precision provided by a discrete sensor, either electrical, acoustic noisemaker, or pulsating pedal is probably not sufficient to bar a vehicle from the highway. If the mileage since onset of the warning were also known, this would allow a more defensible evaluation to be made of the brake life remaining.

If the discrete warning comes at 1000 miles (average) before end of life, it will have different implications for the driver who gets 6 to 10 thousand miles and the one who gets 40 to 60 thousand miles on equivalent linings. It appears that an incremental brake lining wear sensor yielding percentage of lining left (10 to 20% steps) might be more suitable. The incremental indication of wear could yield a wear history if the mileage accrued at each increment were recorded. The wear history could then be used to predict lining end of life.

D. TESTING AND DIAGNOSIS

The flight computers of unmanned spacecraft are exercised by separate computer based testers or support equipment. The testing philosophy is that continual successful operation in the past and present of flight equipment is a trustworthy indication of successful future operation during the mission. This same philosophy is applicable to automotive systems.

The support equipment is a means to apply stimuli to the flight computers and to record and compare the results. The support equipment is not the functional equivalent of the flight equipment. Functional equivalency resides in a very large general purpose computer simulator which emulates the flight computer. This large machine is a third party in the testing and it is used to determine the responses of the flight computer at various internal test points and at the output interfaces to flight computer testing programs.

All phases of the flight computers are simulated by applying inputs and noting the responses. The inputs and responses are recorded on tape and supplied to the support equipment. The support equipment then applies these same inputs to the actual flight computer hardware and records the outputs. A comparison is made with the emulator outputs and agreements or discrepancies noted.

This same procedure is repeated over and over again under a variety of environmental conditions such as temperature extremes, voltage limits, vibration, shock, humidity, and vacuum. The flight equipment is also exposed to environments beyond these limits while nonoperating and then retested when the environment is returned to the normal limits. This environmental testing should weed out the marginal components and further develop confidence in the ability of the flight equipment to withstand hostile environmental conditions.

The safety-telemetry processor in an automobile equipped for automatic highway use is very much akin to the spacecraft support equipment. It should have the ability to apply stimuli to the various subsystem processors by either direct input or by simulation of a sensor input signal. It would then compare the response obtained to that expected and determine if the two were close enough alike to indicate proper operation of the subsystem. The expected results could either be stored in the safety-telemetry processor or in the wayside highway access controller. In either case, these expected subsystem responses would probably have been obtained from a third computer which performed the simulation for all vehicles of a particular type, model or configuration.

If all the subsystem's proper responses were stored on board, the comparison could be done there and a simple signal, indicating everything was all right, could be sent to the roadside. On the other hand, if the expected subsystem responses obtained from the simulator included all those which would be obtained with various malfunctions in the subsystems, the storage capability of the on-board safety-telemetry processor would probably be overwhelmed. It would then seem that roadside computer storage of "malfunctioning subsystem" responses would be more appropriate.

If the safety-telemetry detected an abnormal response from a particular subsystem, this entire response could be sent to the roadside where it would be compared with malfunction responses. If agreement were found, then an error message indicating the malfunction could be generated. If this malfunction were serious enough to deny access to the highway by the vehicle, then it could also be forwarded to the vehicle operator so that corrective action might be initiated.

The foregoing is illustrative of but one possible technique. It may be desirable to have the on-board safety telemetry processor diagnose simple obvious malfunctions and leave the more complicated to the roadside computer. The decision as to which are simple and which complex requires additional criteria.

Regardless of the system configuration or where the proper operation or malfunction decision is made, there are certain restrictions that must be observed in the testing of the various subsystems. This is especially true if the subsystem tests are made "on the fly" and at highway speed. The two critical subsystems are obviously those for lateral and longitudinal guidance. The response to any stimulus of these two systems must be kept small to avoid an unsafe vehicle response or seriously disturbing the manual operator. The diagnosis of the lateral and longitudinal guidance systems will then have to rely on small signal response unless the checkout can be done at very low speed where full-range response testing is practical.

1. Vehicular Electronic Subsystems

Semiconductor electronic circuits and functional elements have found application in four areas in vehicular use (Ref. 39). The first of these, and also the oldest application, being entertainment; radio, both AM and FM stereo, tape systems and radio communications. The other areas are:

(1) Devices which convert driver instructions to actions:

(a) Electronically Sequenced Turn Indicator Flasher.

(b) Constant Speed Control (Cruise Control, Etc.).

(c) Heater-Air Conditioner (Climate) Control.

(d) Intermittent Windshield Wiper.

(2) Devices which regulate or control engine and related operations:

(a) Alternator Rectifiers.

(b) Alternator Regulator.

(c) Electronic Fuel Injection.

(d) Ignition (High Energy, Capacitor Discharge, Transistor Etc.)

(e) Electronic Spark Timing.

(f) Exhaust Gas Recirculator Valve Control.

(g) Emission Control (Lean Burn).

(3) Devices which aid, boost, or assist driver operations and indicators:

(a) Controlled Slip Braking.

(b) Headlight Dipping Control.

(c) Tachometer.

(d) Clock.

(e) Intrusion Alarm.

(f) Electronically Controlled Automatic Transmission.

(g) O.K. Panel.

(h) Headway Sensor (Radar, Optical.)*

(i) Automatic Braking.*

(j) Air Bag Deployment Control.

(k) Electronic Panel Display.*

(l) Driver Information System.*

(m) Impaired Driver Detector.*

With few exceptions, the devices in all categories require sensors that can interface with the electronics and many devices require actuators or switches which can be electronically operated.

Future trends are for microprocessors to control the devices or provide the function. Since the devices are distributed throughout the vehicle, a multiplexed bus system for conveying sensor data to the microprocessor(s) and actuating data to the controllers is currently being studied for automotive application.

Another ramification of this future trend is that the sensors and transducers currently installed temporarily for off-vehicle diagnosis and test equipments, may very well be permanently installed as part of a subsystem. Therefore an on-board diagnosis system becomes a realizable possibility.

2. Safety Telemetry Systems

A basic assumption in automatic highway operations is that only properly equipped and operating vehicles should be allowed entry. Additionally, it is assumed that these determinations will be made, without driver intervention, just prior to entry onto the highway.

The implications of these assumptions are that there is some sort of "automatic checkout" of the vehicle to assure that all subsystems are operating properly and that there is a means for relaying this information to the highway entry controller which makes the decision to grant or withhold access to the vehicle. Further inferences which may be drawn are that there are means to prevent access to unsuitable vehicles and that defensible reasons for not allowing access will be given to the vehicle operator. These latter aspects are not the concern of this effort.

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*R and D Status at Present.

The possible configurations of the on-board checkout and relaying system depend on whether the checkout subsystem will be combined or not with other systems and whether sensor data or only the checkout results will be sent to the roadside highway controller. The latter factor determines the complexity of the on-board checkout or safety telemetry processor.

In the configuration shown in the block diagram of Figure 23, the safety telemetry processor and communication link have been added to the vehicle as separate subsystems. An engine diagnostic processor and transmission controller are assumed to be part of the vehicle electronics. The safety telemetry processor receives data from sensors in the lateral guidance (steering control) subsystem, the longitudinal guidance (speed-braking control) subsystem, as well as from the economy emissions (fuel-timing-egr), engine diagnostic and headway sensing subsystems.

If the safety-telemetry processor is principally a data converter and organizer, then it gathers data from the sensors and other subsystems, converts raw data to engineering units, and formats the information into a standardized form for transmission by the communication link. The standardized form for the data avoids the necessity for identifying each piece of data as to its source or what it represents but places a requirement that the entire message be received error free so that each bit is in the proper place.

On the other hand, if the safety-telemetry processor has decision making capabilities, then it may determine if the various sensor and subsystem parameters are within prescribed limits. It can then provide a summary message for transmission to the roadside highway controller. This summary can be as brief as a few bits indicating all systems are alright to a few words giving the status of all subsystems.

Regardless of the complexity of the safety telemetry processor for handling sensor or subsystem data, it seems that it should also have sufficient ability to respond to requests or commands from the roadside highway controller. This function would be needed for the exercise and diagnosis of all subsystems including the safety-telemetry processor. Connections from the processor to provide forcing functions or stimuli to each of the subsystems would be needed in addition to the subsystems sensor inputs and outputs shared by the safety telemetry. The dynamic response of the lateral and longitudinal guidance subsystems could then be tested by applying a step function to the inputs, for example.

If the safety-telemetry processor is connected to the input and output of the other subsystems, the configuration becomes more like that of Figure 24. The safety-telemetry processor is then effectively in parallel with every other subsystem.

An additional feature of this configuration is a provision for the manual input of historical inspection or repair data. Inspection data such as tread depth when related to mileage and time intervals should allow a more accurate prediction of end of tire life or conversely a reliable estimation of the tires lasting for an additional period. Repair or replacement data if correlated with an operation history of the vehicle should similarly provide more reliable prognostication data.

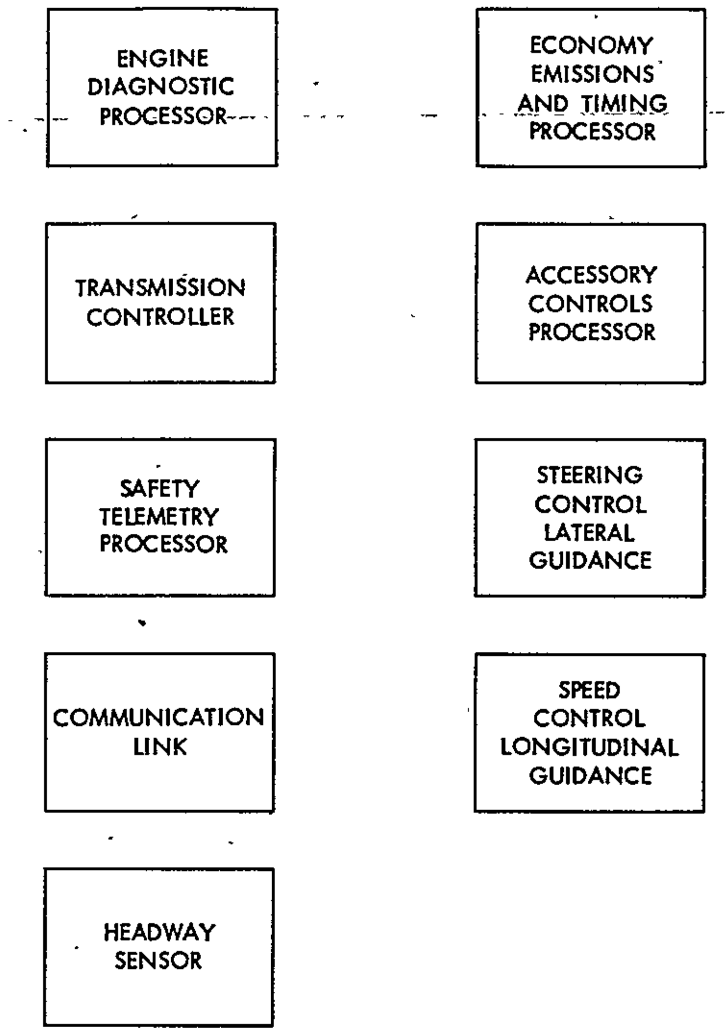

Figure 23. Individual Vehicle Processors

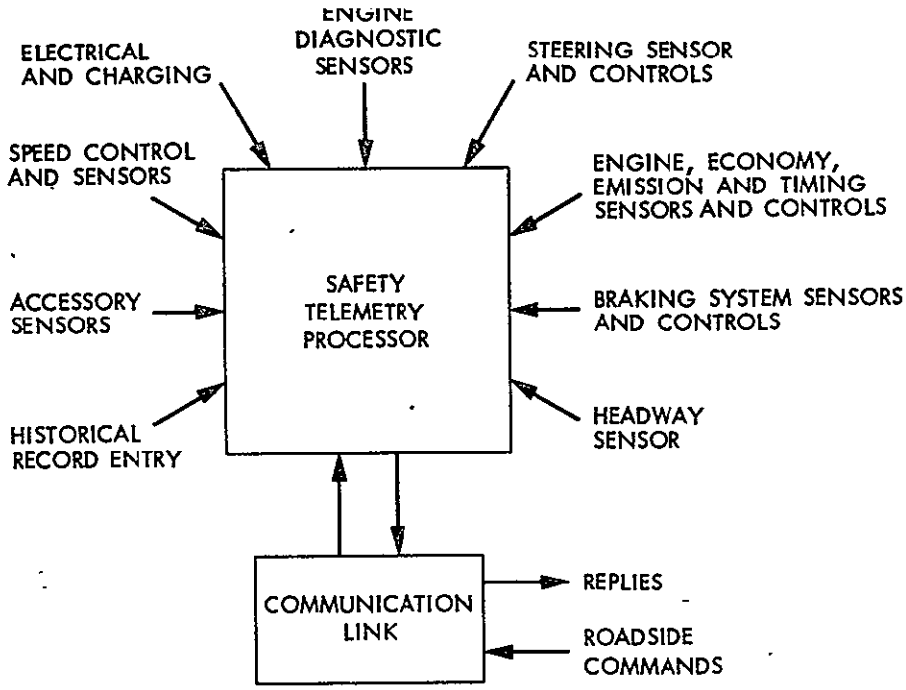

Figure 24. Safety Telemetry Processor - Input Data Only

The operation history could be a time-at-speed-interval histogram which would be important in predicting the remaining life of speed sensitive components such as belts, alternators, water pumps, and drivelines. The operating history acquisition function would require time as an auxiliary input to the safety-telemetry processor.

If the safety-telemetry processor in the Figure 24 configuration is in parallel with each of the other subsystems, two alternative configurations may be supposed. The first would be to combine all processing functions into one central processor as in Figure 25. The second which is less obvious would be to use identical processors for each subsystem as in Figure 26.

The disadvantages of a single central processor are the speed requirements to handle several real-time processes and the concomitant expense and many connections needed for sensor and control. An additional disadvantage is that a highly reliable subsection of this processor must be provided to perform the diagnosis of the remainder of the processor in case of faults.

The use of identical processors, while not necessarily more or less reliable than a single central processor, does simplify repair and parts inventory. There is no particular operational advantage to identical processors over specifically tailored processors if the sensors and

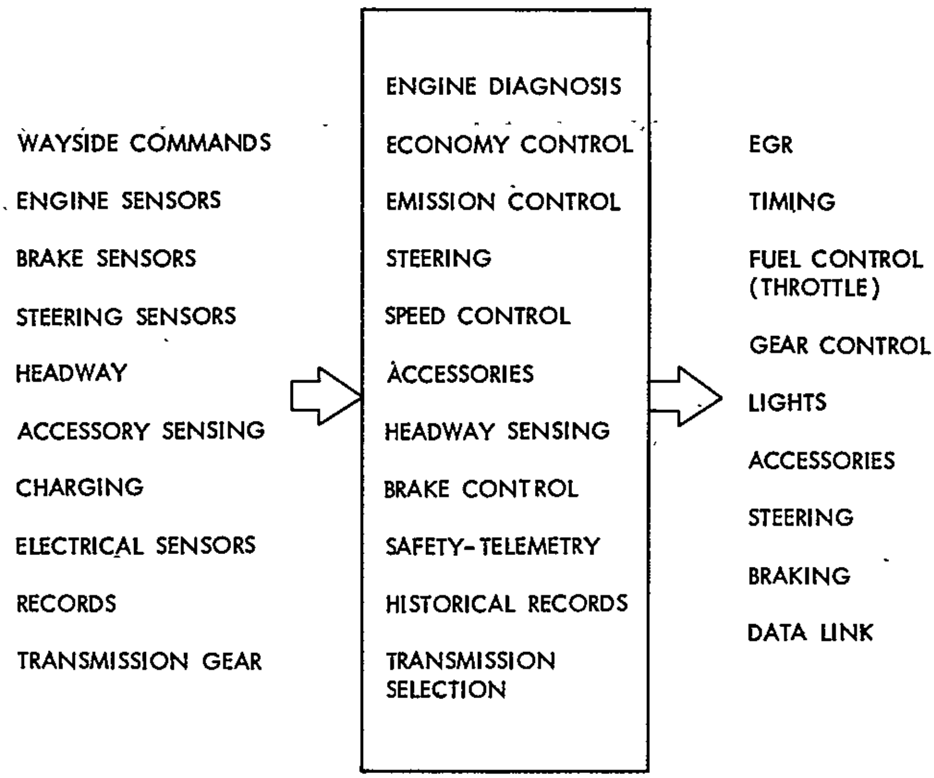

Figure 25. Central Vehicle Processor

controls for each functional subsystem are connected only to a specific processor. To realize the advantages of identical processors, each processor must have access to each sensor and control. This can be accomplished utilizing a bus structure as shown in Figure 27.

The bus structure provides a distributed computing capability where the programs to perform a given subsystem function need not reside in one particular processor. There may also be duplication of critical programs in other processors so that a back-up mode can be used in case of a processor failure. The bus concept requires that some means be provided to selectively switch appropriate sensors and control lines to the input and output buses to sense and control a particular subsystem process. This capability resides in a bus controller which is a computing function residing in one of the processors; most likely the safety-telemetry processor. The actual switching of sensors and control lines requires selectable or addressable switches. The development of such switches is currently being pursued for automotive application.

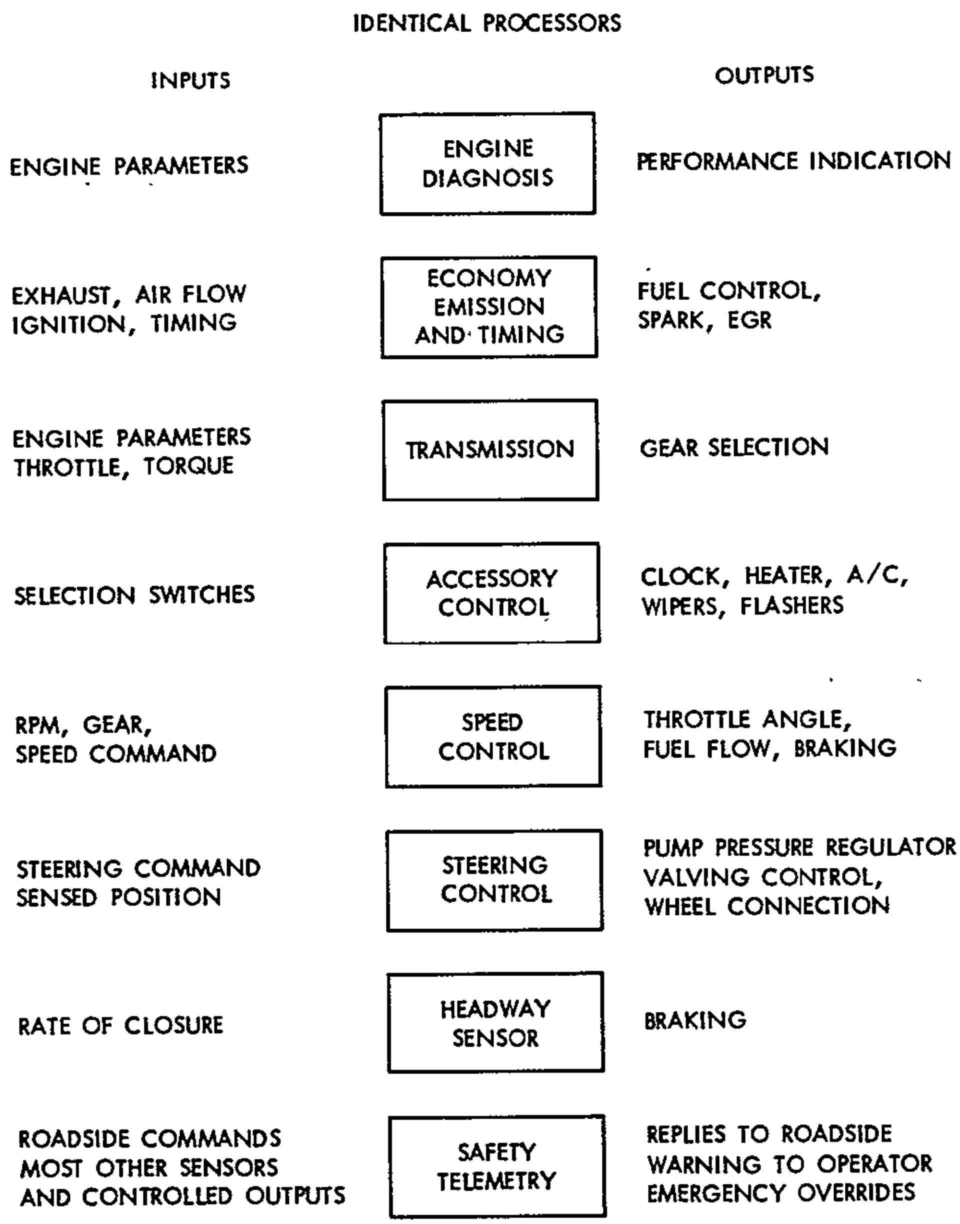

Figure 26. Identical Processors

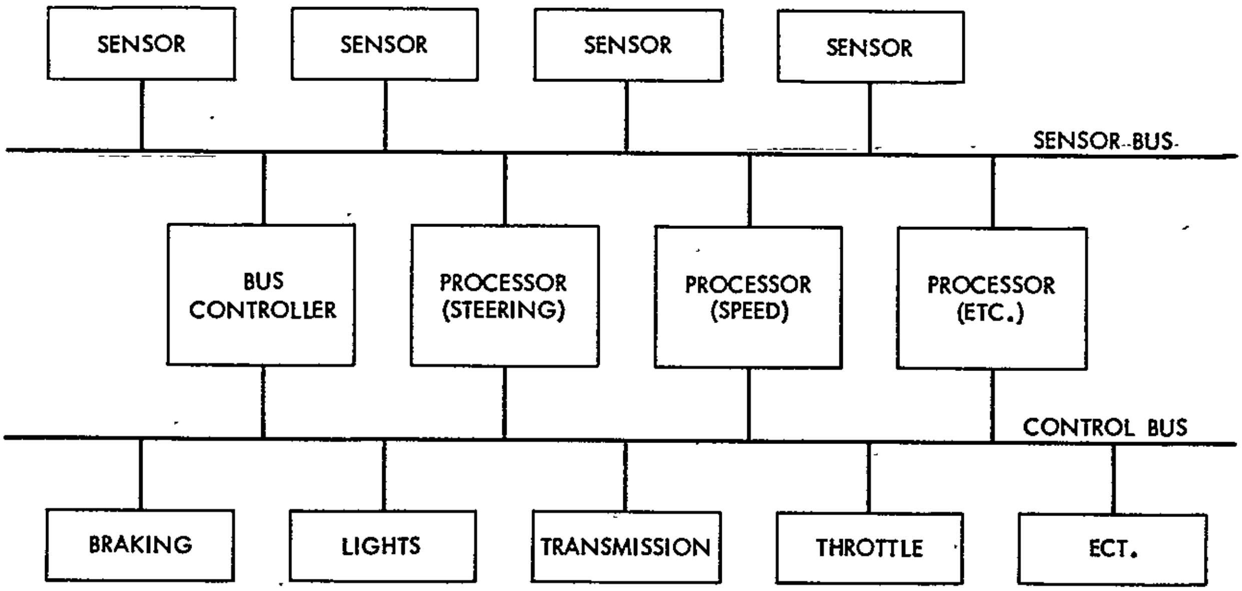

Figure 27. Bus Processor Configuration

The configurations discussed are in the historical order of development of computing systems for aircraft and spacecraft. The current state of the art of computing applications in automobiles is to develop a specific processor for a particular subsystem function with dedicated sensors and controllers hardwired to that processor.

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APPENDIX

SURVEY OF AUTOMOTIVE SENSORS

R. S. Rogero

The primary concern of those involved in automotive sensor development today is in providing sensors that can be economically used in conjunction with engine controls designed to permit auto manufacturers to meet current emission and fuel economy requirements. There is no reason, however, why those same sensors, or the transduction techniques employed by them, could not be used to monitor parameters that are determined to be critical in judging whether or not a vehicle could enter an automated highway.

1. PRESSURE

a. Major Types of Pressure Sensors (Transduction Techniques)

There are five basic types of sensors in use or development for the automotive industry today. A brief description with some advantages and disadvantages follows:

1) <u>Variable Reluctance</u>. This type of transduction operates on the principle of changing the gap in the magnetic flux path, and thereby varying the magnetic reluctance, as a diaphragm moves in response to an applied pressure. The inductance ratio is measured by an ac bridge circuit in which an output voltage proportional to pressure is obtained. Demodulation following the suppressed carrier bridge output is required for a dc signal. The linear variable differential transformer (LVDT) is an electro-mechanical transducer which produces a voltage output directly proportional to the displacement of a movable armature or magnetic core. The core is axially positioned inside three transformer coils consisting of a primary with two secondaries connected in series opposite. By energizing the primary with alternating current, a voltage output appears across the secondary circuit when the magnetic core is moved from the central or null position.

2) <u>Variable Capacitance</u>. Sensors employing variable capacitance as the means of transduction generally vary the distance (and the capacitance) between parallel plates, where one plate is rigidly located and the other free to move as pressure is applied. An electronics package containing an oscillator, capacitance, bridge, demodulator and amplifier is required to convert the varying capacitance into a dc voltage (Ref. A-1).

3) <u>Semiconductor</u>. The transduction element for this type of sensor is formed by gas diffusion of piezoresistive sensing elements on an etched silicone crystal diaphragm. The temperature compensation resistors, voltage regulation, and amplification required to support the sensor can be located on the diaphragm periphery or adjacent to it (Ref. A-2).

4) Strain Gage. Conventional strain gage transducers consist of metallic wire networks attached to a pressure flexible diaphragm. As the diaphragm is flexed the resistance of the attached strain gage is changed. This change in resistance is measured and converted to a proportional dc voltage by means of a resistance (Wheatstone) bridge arrangement along with various compensating and amplifying electronics.

5) Crystal. This type of sensor contains a crystal whose frequency of oscillation varies with pressure induced stress. One advantage over other types of transduction is that this signal is directly compatible with digital processing since the frequency of the signal is proportional to pressure (Ref. A-3).

Each of these techniques is used to make accurate pressure measurements and have been employed in various types of automotive diagnostic equipment, especially where the sensors are attached to the vehicle at the time of checkout. However, for permanent installation on large numbers of automobiles the situation is somewhat different.

Currently, and for the near future (one to two model years), the sensors that appear to have been accepted are: variable reluctance types for 1978 and variable compacitance for 1979, although some semiconductor sensors will no doubt be used on 1979 cars. The 1980-81 models, however, will most likely see a complete dominance by semiconductor sensors. The reason is simple enough - up to now, semiconductor transduction techniques have not been able to meet the price and specification requirements of the automotive manufacturers. Improvements in technology have brought that capability to the point where it is attainable without the expenditure of great amounts of time or money. This increased capability on the part of semiconductor sensors coupled with the inherent (albeit greatly improved) complexity, by comparison, of other types of transduction makes the current trend towards the semiconductor sensor appear to be irreversible.

b. Pressure Measurement Applications

Pressure measures in both hydraulic and pneumatic application and in differential and absolute (or gauge) forms are needed for both spark and combustion ignition engines. A list of present and future measurements and applications is presented in Table A-1.

Current methods of measuring pressure precisely as in off-vehicle diagnostic equipment use both the LVDT (low voltage differential transformer) and semiconductor strain gauge devices with integral amplifiers. The LVDT units cost $250 and up while the semiconductor devices are less than $20. On-board pressure sensors often use diaphragm controlled rheostats where an analog voltage is required.

c. Tire Pressure Monitor

Among the various reasons for remote, automatic determination of automobile tire pressure is the development of the "run flat" tire.

Table A-1. Pressure Measurement Applications

1. Monitoring intake manifold absolute pressure for on-board diagnostics.

2. Intake flow measurement by monitoring intake venturi pressure drop.

3. Intake port mass flow sensing by using a combination barometric pressure and pressure drop at the intake manifold throttle valve or using manifold absolute pressure combined with pressure drop at the throttle valve.

4. Manifold pressure sensing for electronic fuel control (for either electronic fuel injection or electronically controlled carburetion).

5. Manifold pressure sensing for electronic ignition advance.

6. EGR flow measurement.

7. Monitoring engine oil pressure.

8. Sensing fuel pump output (with possible adaptive control) for fuel line pressure control or rate of consumption monitoring.

9. Monitoring turbocharger output in special emissions engines and in industrial truck engine applications.

10. Barometric pressure sensing for altitude compensation (fuel control).

11. Monitoring hydraulic and vacuum boost systems for accessory drives (particularly for detecting failure modes in safety related accessories.).

12. Monitoring engine and chasis performance points for on-board diagnostics.

13. Monitor of pressure reservoir for crash air bag.

14. Measurement of pressure transients in fore and aft energy absorption system for crash detection (air-bag deployment).

15. Tire pressure monitor.

16. Monitoring the performance of the brake pressure assist systems.

17. Input for electronic hydraulic suspension control system (for anti nose-dive/anti-sway control).

18. Measurement of transmission fluid pressure for electronic shift control.

19. Sensing driver demand for brake system operation and brake line pressure.

Table A-1. Pressure Measurement Applications (Continuation 1)

20.	Anti-skid control by direct adaptive sensing of the brake line pressure either at the master cylinder or at the brake caliper/brake shoe pressure application points.
21.	Turbocharger output to determine engine output and fuel demand.

This tire, designed to eliminate the need for spare tires, permits a vehicle to be driven some 50 miles at speeds up to 50 mph without damage to the tire. Early reports of the handling characteristics of prototypes indicate that, at least with rear mounted tires, the driver cannot tell when he has a flat. He could thus, if not warned, drive the tire to destruction before he became aware of the condition.

Other results of not knowing a low-tire-pressure condition might be less spectacular, but could affect tire wear as well as vehicle handling characteristics.

There have been several attempts at marketing devices to monitor tire pressure, but as yet none have been successful from the auto manufacturer's viewpoint because of technical problems, cost or both.

One device that could be close to acceptance, especially if installation were legally required has been developed by AVCO. It works as follows:

An electromechanical system consisting of a sensor and a transmitter are mounted inside each tire. Completing the system are a pickup antenna mounted inside each wheel well, a radio receiver mounted in any convenient place, and a warning light or buzzer visible or audible to the driver.

The sensor/transmitter consists of a fluidic transducer monitoring the tire pressure and a small radio transmitter that sends a coded warning when pressure drops below a preset point. The radio transmitter is a self-pulsed oscillator operation in the citizens' band. The receiving or pickup antenna, mounted to a ground plane, consists of a printed-circuit board coil housed in a plastic case. Two rf-amplifier stages make up the receiver. The receiver amplifies the coded rf signals, decodes and amplifies the audio signal, and energizes a warning light or buzzer for the driver.

The sensor/transmitter uses no electrical power unless low pressure is sensed, and then uses less than the standard auto clock.

2. TEMPERATURE

a. Major Types of Temperature Sensors (Transduction Techniques)

1) Thermistors. These devices are temperature sensitive resistors with a high (usually negative) TCR (temperature coefficient of resistance. Thermistors can be used over the temperature range from (-) 100°F to (+) 600°F. They are cheap and dependable, but are also nonlinear and in some cases the negative TCR is undesirable.

2) Platinum Resistance Bulbs. A coil of strain free, high purity platinum wire, they are usually used in a Wheatstone bridge circuit to give a linear output with a positive slope. Their useful range is - 435°F to + 1800°F. They are more expensive than thermistors, but have their greatest applications in extreme environmental conditions or where higher precision measurements are required. Sensors which operate in the same manner are sometimes constructed using nickel as the temperature sensitive metal. The physical configuration can be in various forms from that similar to a strain gage to a wound bobbin in a brass probe.

3) Semiconductor Temperature Sensors. There has been considerable progress in the development of integrated circuit sensors utilizing the temperature sensitive properties of silicone as the transduction method. Several devices are currently on the market which give high level 10 millivolt/°K outputs over the range from -55°c to +200°c in the under $1/unit price range. This field is relatively new and seems to be expanding (Ref. A-4).

In some cases semiconductor pressure transducers can be used to measure temperature where space or number of available leads is a concern. To do this the pressure sensor is used in a constant current mode and variations in bridge voltage are measured and converted into temperature information. It is also relatively easy to incorporate a separate temperature sensitive resistor on the pressure measuring chip, where desirable.

Temperature measurements on vehicles are primarily for determining if proper lubrication and cooling are being maintained in the engine and drive line. Air conditioner and heater measurements often aid in diagnosing proper operation. Table A-2 is a list of temperature measurements for both buses and cars. The temperature sensor most often used is the platinum resistance type. This device has excellent repeatbility and linearity. Bimetallic elements are used where a mechanical interface is needed. On-board sensors where an electrical interface is required use thermistors and resistance thermometers. The direct operated gauge, used with an expansion bulb sensor, finds little use except in after market coolant temperature gauges.

Table A-2. Temperature Measurements

Power	Air Conditioner and Heater
Engine Coolant	Air Supply
Lubrication Oil	Return Duct
Transmission Oil	Compartment Air
Differential Oil	Evaporator Inlet
Intake Manifold Air	Evaporator Discharge
Catalyser Bed	Condenser Inlet
	Condenser Discharge
	Expansion Bulb
	Compressor Head
	Compressor Crankcase

3. SPECIAL DEVICES

a. Automatic Tire Inspection

Southwest Research Institute has developed a drive-through tire inspection system which can detect carcass flaws, determine tread depth, and set inflation pressure. The prototype developed in a program for NHTSA, is intended for use in either assembly-line inspection stations or as part of vehicle safety diagnostic equipment.

The machine is designed to check two tires, mounted on a vehicle, simultaneously. The vehicle is rolled into place, with a pair of its tires resting on test rollers. Tire carcass integrity is checked by mechanical vibration; as the tires are rotated slowly by the rollers, electrodynamic shaker rods apply wideband random excitation to the tread centerlines. These 100-400 Hz vibrations set up resonance in the tire which is sensed by transducers placed in contact with the side-walls. Defects such as tread chunking, uneven wear, broken tread, or separation affect local resonance patterns, and thus, flawed regions of the carcass present characteristic responses. The system is capable of detecting a wide range of significant tire flaws.

Tread depth is measured as the tires roll over 10-in.-wide arrays of 400 finewire probes. These latter are extended pneumatically to trace tread profiles. Tread condition is recorded, and compared to computer-stored criteria. The tire pressure portion of the inspection is carried out by use of an inflation device, which functions automatically once attached manually to the tire valve stem.

This device measures tire pressure, then inflates or deflates to a level specified by computer. The result is that when the tire stabilizes to a specific "cold" temperature, it will have a specific "cold" pressure within ± 2 psi. The prototype machine can perform an inspection of 2 tires in about 2 minutes.

The system is envisioned as part of an overall vehicle inspection station, one that would perform automated inspection of tires, brakes, steering, and suspension components (Ref. A-5).

b. Throttle-Position Sensor

The primary thrust in this area is on potentiometric devices. With the improvements made in recent years, the problems associated with the wear of sliding contacts have been alleviated to a point where meeting life requirements of over 1,000,000 full cycles and 10,000,000 dithers is well within the reach of present-day technology.

c. Crankshaft-Position Sensor

Typically, engine speed and position signals are derived from the distributor. However, the tolerance stack-up associated with the multiple linkages that exist between the crankshaft and the distributor shaft necessitates that engine speed and position information be obtained from the crankshaft itself to increase measurement precision. Considerations relating to the environment in which the sensor must be located lead to the selection of a variable-reluctance concept.

A unique feature of this design is that the sensor detects holes in a rotating member. The use of a rare-earth magnet makes it possible to considerably reduce sensor size.

REFERENCES FOR APPENDIX

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A-5. J. E. Johnson and L. H. Emery "Nondestructive Testing of On-Vehicle Tires Using Random Mechanical Excitation", "Passenger Vehicle Tire Inspection Equipment Development". (These papers have not yet been published, but should be available soon from Southwest Research Institute, San Antonio, Texas.

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