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ABSTRACT

When Renault and American Motors Corporation joined forces to introduce the 1983 Alliance, they decided to add one uniquely American feature, a highly responsive, low cost electronic fuel injection system. Bendix was selected to develop the fuel controls for the 1.4-liter engine utilizing an innovative single point system concept. The high precision fuel injection system makes the Alliance one of the most fuel efficient cars manufactured in America. With the Bendix system, the small engine produces solid performance and meets EPA emission standards with a relatively small catalytic converter.

The Bendix system consists of a multiprocessor electronic control unit, a throttle body assembly including a single point injector, pressure regulator and an idle speed actuator, a low pressure fuel pump, a manifold pressure sensor, and two temperature sensors. Adaptive control, automatic idle speed regulation, and on-board diagnostics are some of the features that distinguish the system as an advanced engine control system. Modern digital electronic technology makes possible a base system that is easily adapted to a variety of vehicles.

IN 1956 BENDIX BUILT THE ELECTROJECTOR, the first electronic fuel injection system. Patents were awarded for the design, but the state-of-the-art in electronics had not progressed sufficiently to permit a practical implementation of the concept. Furthermore, the market conditions were not appropriate for accepting the benefits provided by fuel injection.

With the introduction of the first EPA standards in the early 70's, interest in EFI was revived in an attempt to meet the emission requirements and retain good performance. Early production systems were typically high cost multipoint systems limited mainly to luxury and specialty applications. As the emission standards were progressively tightened and the Corporate Average Fuel Economy standards added, the attraction of EFI increased.

In 1980 a first effort was made to reduce the cost of fuel injection while maintaining its benefits. A throttle body single point injection system was introduced but the application was still to luxury cars. A fuel injection system for base line vehicles was not yet available. That year, Bendix and Renault embarked on a program to apply fuel injection to a compact base line car. In spite of high performance requirements and stringent cost targets, the objectives of this development were met. Fuel economy surpassed the performance of a multipoint system offered on the same vehicle with comparable emission numbers. Driveability comparisons to the multipoint system are favorable with superior cold start performance. These achievements are particularly notable since they were obtained with a system having a significant cost advantage over the competitive multipoint system. The system has been applied to smaller and larger engines and in each case, only simple calibration changes were required. Thus, the system described in this paper has demonstrated its versatility as a base fuel injection system for the car lines of the 1980's.

SYSTEM DESCRIPTION

The new Bendix fuel injection system combines low pressure single point above-the-blade fuel delivery with a closed loop speed-density control strategy. A diagram of the system components is shown in Figure 1. Inputs from temperature, manifold air pressure, and oxygen sensors plus a number of control switches and a tachometer signal are the basis of the air fuel mixture computation by the electronic control unit (ECU). In turn, the ECU controls fuel metering through a single point injector in the throttle body assembly. This assembly also includes an integral pressure regulator and an idle speed control actuator. A low pressure in-tank fuel pump delivers the fuel to the throttle body

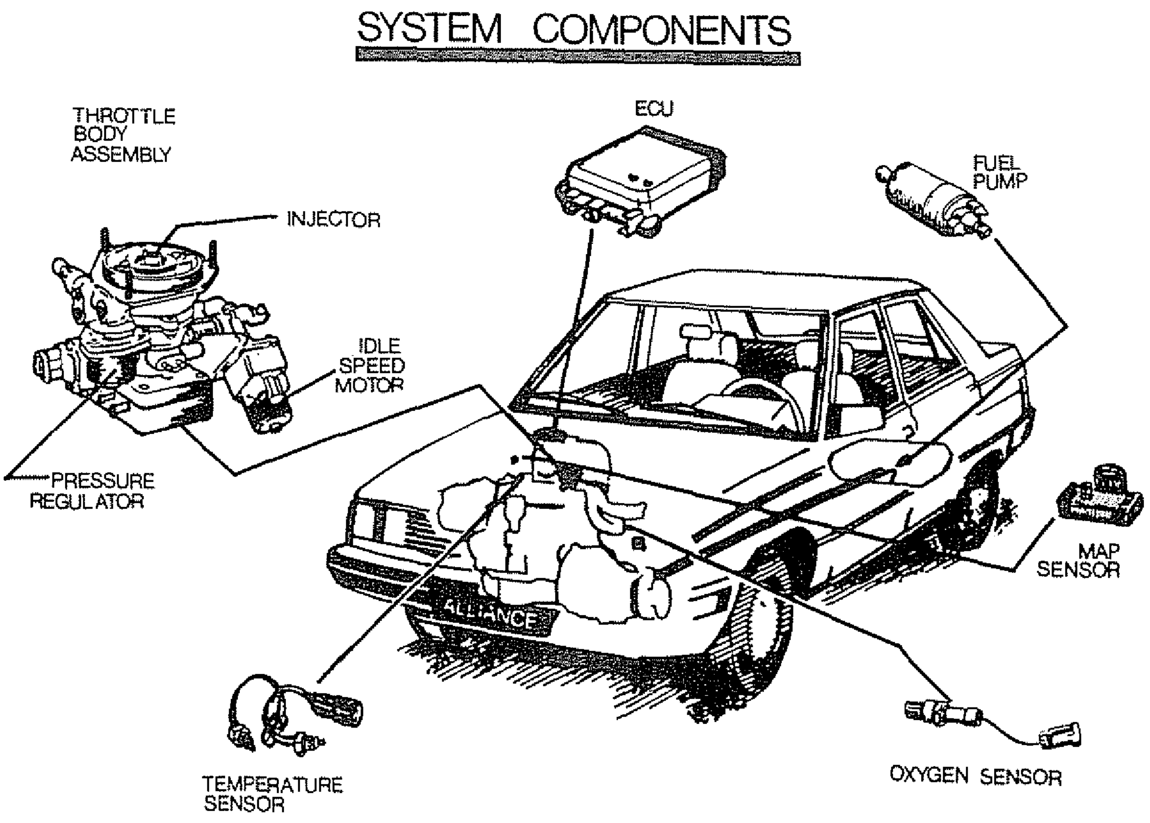


Fig. 1 Bendix Single Point Injection System

assembly. The major components described implement the Bendix single point injection (SPI) system. A detailed discussion of each component follows.

ELECTRONIC CONTROL UNIT - The ECU is a compact single printed circuit board unit as shown in Figure 2. It was planned as a software system for maximum flexibility and minimum component count. The flexibility simplifies the application to a variety of vehicles. The low component count not only minimizes cost but provides the significant benefit of improving system reliability.

A two-microprocessor architecture with a personality PROM was used as the basis for implementing the ECU. This approach provided several benefits over a single unit with added memory chips and was cost competitive. Most significantly, external interface hardware was minimized by the extra ports and timers included in the basic microprocessor chips. Also computation speed was enhanced with the parallel processing capability. The personality PROM which is programmed during ECU assembly contains the system calibration information, allowing early software mask release consistent with production schedules. The power of this PROM was demonstrated by applying the system to other similar engines using the production masked software.

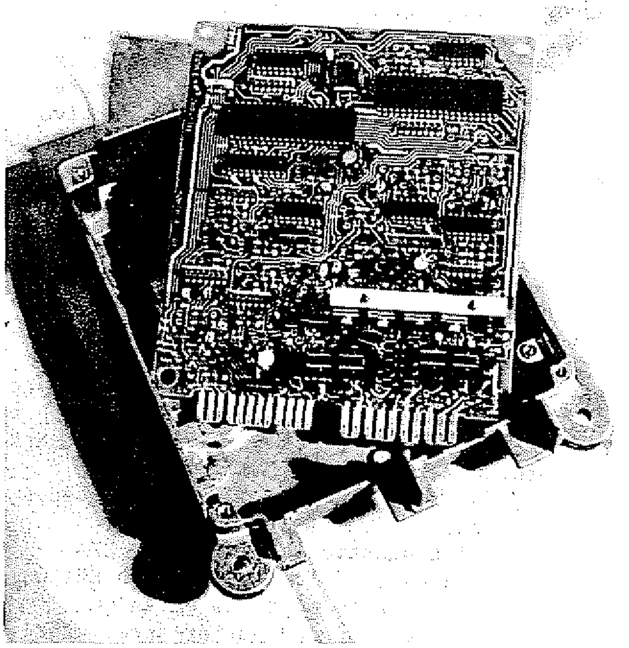


Fig. 2 Electronic Control Unit

A block diagram of the ECU is shown in Figure 3. Microprocessor labeled "A" calculates the fuel pulse width and controls the fuel injector. It interfaces with the analog-to-digital data conversion circuitry and stores information on five analog plus six discrete signals. A tachometer signal is used as the trigger. Manifold as well as ambient barometric pressure is measured with a standard semiconductor strain gage pressure sensor. Coolant and charge temperature (intake air/fuel mixture) are monitored by identical thermistor-type temperature sensors. The oxygen sensor is a standard Zirconia-type unit.

The second MPU labeled "B" is the idle speed control microprocessor. It processes converted analog data from MPU "A" plus other input data to control the closed throttle limit, EGR, canister purge, and the fuel pump relays. Microprocessor "B" also modifies ignition timing under certain operating conditions. The throttle limit function provides a number of features in addition to normal idle control. Included are a dashpot function on deceleration, fast idle for engine starting and warm-up, idle set point control as a function of transmission position and air conditioner operation, and automatic throttle angle control for minimizing emissions on decelerations.

A unique feature in the ECU is a system latch which maintains power for a few seconds after the ignition is turned off. This allows a controlled power down sequence including a throttle actuator extend for repeatable start conditions and the measurement of barometric pressure. The main power supply provides efficient solutions to low voltage operation, reverse battery protection, and controlled system reset. The A/D converter is implemented with a low cost linear subsystem interfaced to one of the timer functions in the microprocessor. A peak and hold circuit is used for the injector driver to minimize injector turn-on and turn-off times. Other output circuits for the fuel pump, EGR, and canister purge solenoids, diagnostic lamp, and discrete spark advance signals are

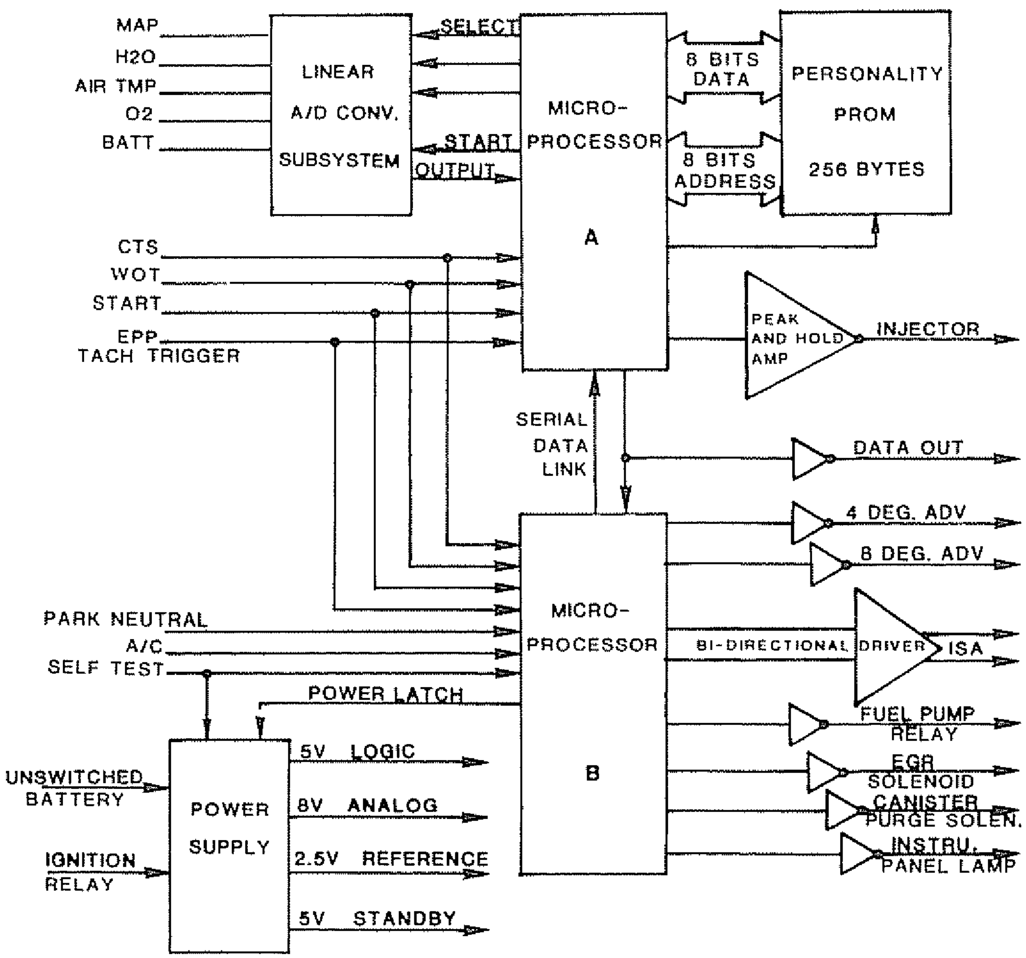


Fig. 3 ECU Block Diagram

open collector drivers matched to the loads and sufficiently rugged to survive normal abuse. The interface to the reversible DC motor idle speed actuator is a bi-directional driver.

The Bendix ECU includes an adaptive control feature that learns the condition of the engine components and makes an automatic adjustment to the open loop fuel schedules. It thus compensates for fuel mixture variations resulting from production component tolerances and engine wear, minimizing their impact on performance and emissions. The adpative control strategy has been shown to be effective and stable under all operating conditions including transients. Also included in the Bendix ECU is an on-board diagnostic system which can be read with a separate lamp. System anomalies are automatically stored as they occur in a continuously powered back-up memory.

FUEL DELIVERY SUBSYSTEM - The fuel delivery subsystem includes an in-tank fuel pump and a throttle body assembly. This system meters fuel into the engine at a constant low pressure. The fuel pump shown in Figure 4 is an electric motor driven roller vane pump. Its on/off operation is controlled by the ECU through a relay.

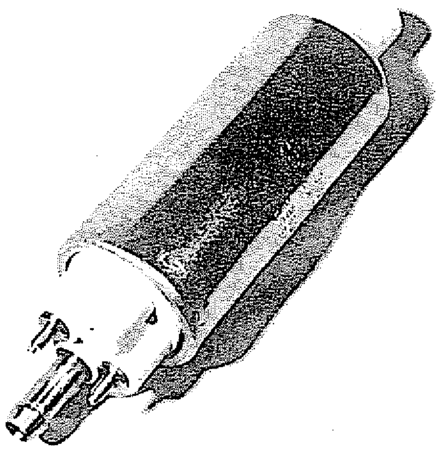


Fig. 4 Low Pressure Fuel Pump

The throttle body assembly shown in Figure 5 includes an integral fuel pressure regulator and fuel injector which are tested individually and as a unit. Ports are provided for PCV, EGR, MAP, and canister purge. The pressure regulator is a diaphragm-operated relief valve set by a preload spring and referenced to the air pressure at the tip of the injector. Figure 6 shows the injector, a bottom feed, low pressure design. Flow of gasoline through the injector is proportional to the pulse width applied to the injector. The control unit compensates for the actuation offset, which is a function of battery voltage. Tolerances in the injector and regulator are adjusted by the adaptive control algorithms in the software.

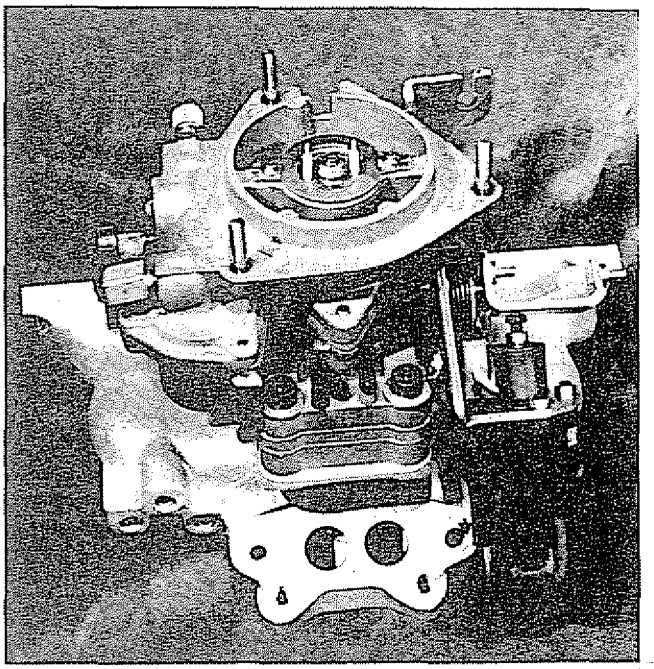


Fig. 5 Throttle Body Assembly

An idle speed control actuator is interfaced to the ECU enabling the processor to provide closed loop idle speed control as well as the functions of dashpot and A/C solenoid. The actuator is a DC motor and worm drive assembly with an integral closed throttle switch. In operation it is electrically positioned to vary closed throttle air flow.

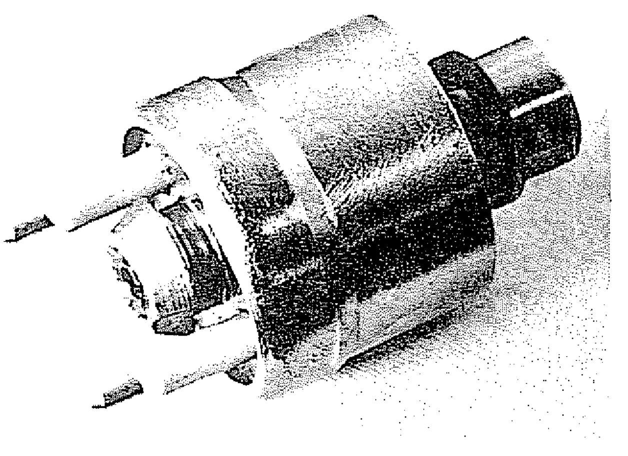


Fig. 6 Bottom Feed Single Point Injector

SOFTWARE DEVELOPMENT

Proven control laws from previous production systems were the starting point for software development. Significant improvements, however, were made possible by the power of the multiprocessor architecture. The system designers were allowed the flexibility of continually refining existing control laws and developing new ones throughout the calibration development cycle.

The programmability of the system presented opportunities to experiment with a variety of potential strategies to improve driveability, increase fuel economy, and reduce emissions. Since hardware was not affected, schedules were not jeopardized by even significant changes. For example, an acceleration enrichment strategy that is a non-linear function of temperature with a temperature-varying exponential decay rate with engine revolutions could be tested in a matter of hours.

To provide a high level of flexibility, the microprocessor system must be sufficiently powerful. The dual microprocessor approach was a judicious system selection since it enabled the efficient use of available memory and a high computational update rate. The total system memory included 4K of Read Only Memory (ROM) for program storage, 256 words of Random Access Memory (RAM) for variable storage, and a 256-word programmable ROM for system calibration constants. Considerable attention was paid to generating efficient code allowing maximum utilization of the available memory. Figure 7 shows the approximate allocation of ROM for the key functions in the final software configuration. Over 50 percent of the memory was devoted to basic fuel and air control functions. Overhead software was kept to a minimum. The system was released with approximately 10 percent reserved space in each microprocessor to simplify future expansions of some of the functions.

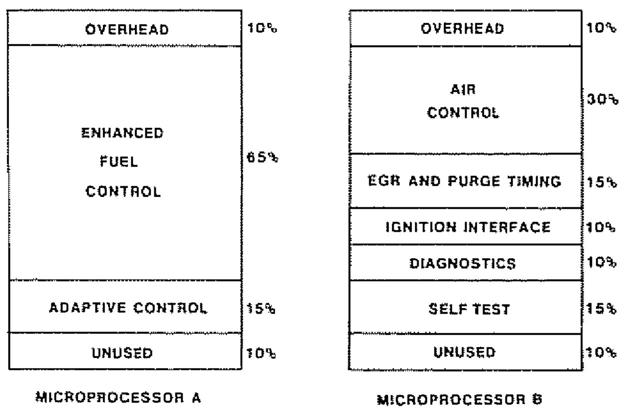


Fig. 7 Memory Allocation

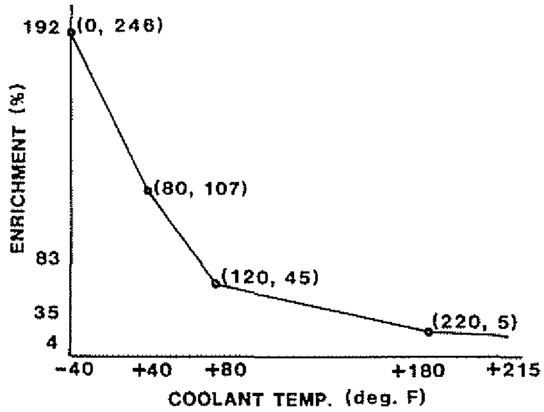
In the course of software development, compromises are made to improve memory utilization efficiency and reduce execution times. For example, in the system a requirement for pulse width scaling by a normalized binary fraction occurs repetitively. An eight by sixteen multiply was not sufficiently accurate for some calculations. A standard sixteen by sixteen multiply routine was not needed and it is relatively costly in code and execution time. Thus, a nine by sixteen bit multiplication reentrant subroutine was written to meet the system requirements.

The Bendix SPI system is an interrupt driven system. Software efficiency was, therefore, greatly increased by writing all the subroutines as reentrant code. Often the same type of operation is required in the interrupt service routine as in the continually running background routine. When execution of the interrupt routine is complete, the environment is restored and the original execution can proceed.

Efficient program code is of limited value if the system is not user friendly. In this case, "user friendliness" refers to the ease of system calibration provided to the application engineer. In the Bendix system, all the calibration constants for the control laws are contained in a 256-byte personality PROM. The efficiency standards that govern the development of the program code extend as well to this PROM. We determined that the most efficient way to represent a non-linear function in an EFI system is by means of table lookup and linear interpolation. All table entries are coordinate pairs representing the breakpoints of a piecewise linear curve of the desired function. A typical curve is shown in Figure 8. One software routine performs the lookup of an arbitrary number of breakpoints and interpolation between adjacent pairs. The starting point of the curve is wired into the software by means of an assembly label. The endpoint is signalled by a decrease in the stored independent variable. Thus with some acceptable restriction on the byte following a table listing, we have developed the most efficient use of the space allocated for calibration data and the most flexibility for the application engineer.

CALIBRATION DEVELOPMENT

Based on the extraordinary goals established, the application of the Bendix SPI system to the 1983 Alliance presented a significant challenge. Fuel economy targets were high and the ultimate goal was to achieve certification with acceptable driveability using a small economical catalytic converter. A highly precise calibration was, therefore, needed. The ambitious fuel economy targets dictated high spark advance and aggressive shift schedules. The shift schedule presented a problem of driveability during warm-up, which was addressed by good fuel calibration.



PERSONALITY PROM ENTRIES

START ADDRESS	0	X1
	246	Y1
	80	X2
	107	Y2
	120	X3
	45	Y3
	220	X4
TOP OF TABLE	5	Y4

RANGE RESTRICTION -( )- DATA ENTERED MUST BE <X4

Fig. 8 Typical Stored Curve

Adding a small amount of EGR provided NOX control without compromising the spark. The effect of EGR on fuel control was compensated with a rate calibration constant.

A key to system optimization is a successful adaptive control strategy. With open loop operation calibrated to be nominally stoichiometric, the average closed loop correction on a given production system is an indication of the system deviations from nominal. This information enables the system to automatically make adjustments for normal expected tolerances to the authority limit set by the applications engineer. Fuel schedules can thus be closely trimmed to meet emissions and driveability goals while minimizing fuel consumption.

Particular attention was paid to hot engine operation in low air temperature and/or high altitude conditions. The refinement of the hot calibration involved extensive study of acceleration enrichment and deceleration lean-out. The first includes a continuing balance between driveability and emissions with special consideration during shift maneuvers. Deceleration lean-out minimizes potential rich manifold conditions which could cause excessive loop corrections.

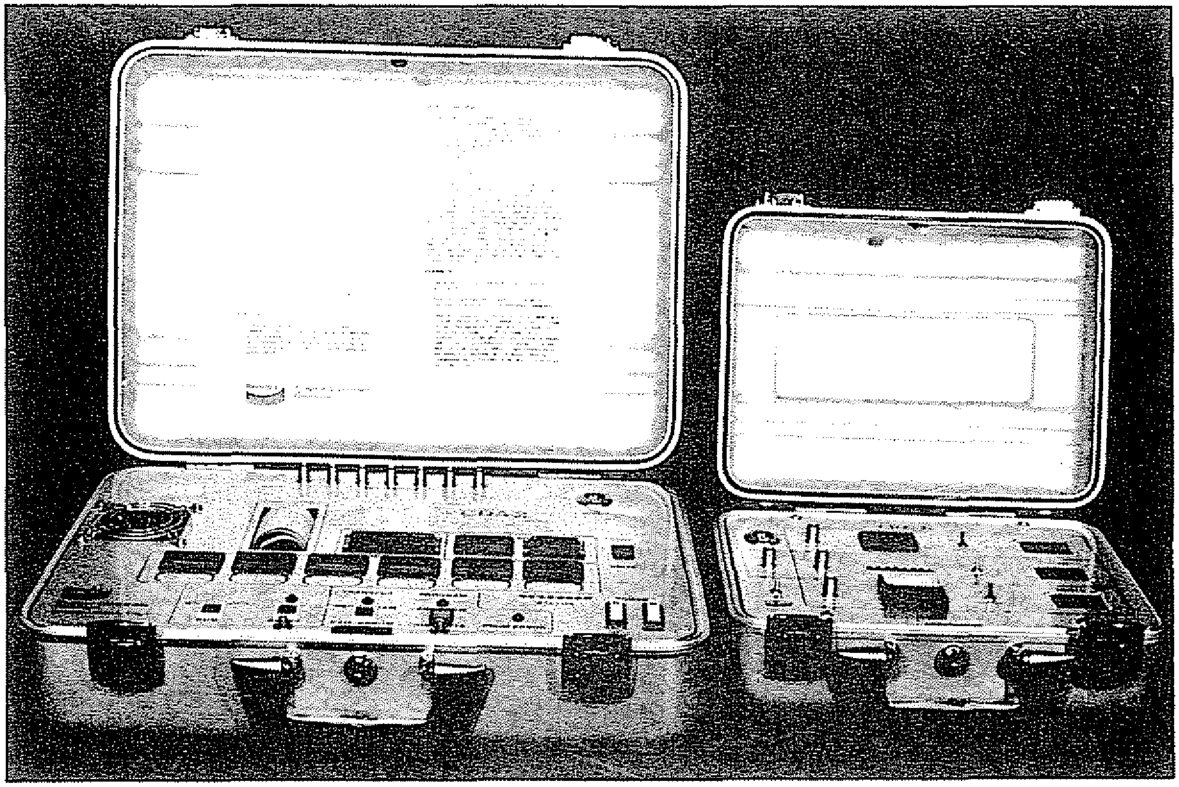
Cold start calibration required close control of EGR enable, spark schedule, loop closing, and canister purge. Proper instrumentation of each cold start was simplified with the Bendix ECU. It directly provides calibration and diagnostic information from a serial data link which is easily interfaced with display and recording equipment. Records after each start facilitate optimal calibration for best emission control during warm-up. Calibration development at extreme temperatures concentrated on providing clean starts and good driveability. Because temperatures are processed as analog quantities, there are no discontinuities in warm-up fuel enrichment. Good drive-away performance is thus experienced at all temperatures. Various trips to temperature and altitude extremes were conducted during the course of the calibration development to refine the good driveability of the vehicle. System versatility was highlighted during repeated tests. Adjustments to performance under one extreme condition could be implemented without affecting base line performance.

System calibration was greatly facilitated by the development aids shown in Figure 9. Figure 9a shows the basic calibration development aid used to monitor system operation and modify programs in real time. The unit is highly useful in the early stages of system development. A more transportable instrument is shown in Figure 9b. This calibration aid can be used to continuously monitor three channels of information as selected by the operator. It interfaces directly with the serial data link in the ECU and provides both digital and analog outputs. This instrument was an important tool in the later stages of calibration development especially during the various trips.

SYSTEM PERFORMANCE

The Bendix single point fuel injection system was easily certified with typically a 30% margin on emission numbers. These results were achieved with a relatively low cost single three-way catalytic converter. The vehicle fuel economy is one of the best of its class. Ratings are 52 MPG highway and 37 EPA. Along with good fuel economy and emission performance, the Alliance has excellent driveability. The car starts well under all temperature conditions and remains strong during warm-up with no stall problems. Furthermore, acceleration is surprising for the small engine displacement used in the vehicle.

To ensure that system performance is properly maintained in the field, the custom diagnostic tester shown in Figure 10 was developed. This tester connects to the diagnostic tap in the vehicle and can be used to verify system operation. The unit will not only isolate potential faults in the complete SPI fuel system, but also field tests the ECU. All tests require the use of only three interface switches with a majority of the diagnosis performed from the passenger compartment. Messages are displayed



(a) Basic Instrument (b) Compact Instrument

Fig. 9 Calibration Development Aids

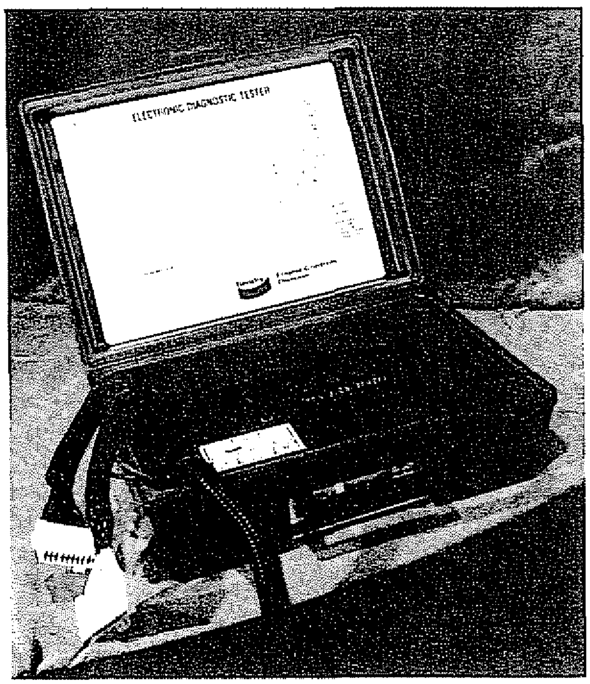


Fig. 10 Diagnostic Tester

on a vacuum fluorescent display instructing the diagnostic technician on the proper steps required to isolate faulty components. The tester is microprocessor-based with a total memory capacity of 48K and 24 input and output lines. It can easily be programmed to accommodate future system modifications or expansions. In fact, the testers have been supplied with both English and French message displays.

SUMMARY

The single point fuel injection system developed by Bendix provides a cost effective fuel control system for base vehicles including relatively low volume lines. Since it is principally a software system, it can be easily modified to meet new requirements. For example, fuel consumption data can be transmitted to trip computers, ignition controls can be added, and diagnostic capabilities can be extended. Future generations of the system with electronics integrated into the throttle body could even be considered for after-market carburetor replacement. The base system described is a highly reliable approach to engine management, easily adapted to a wide range of applications and offering features previously not available on standard economy cars.

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