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Automotive Sensors

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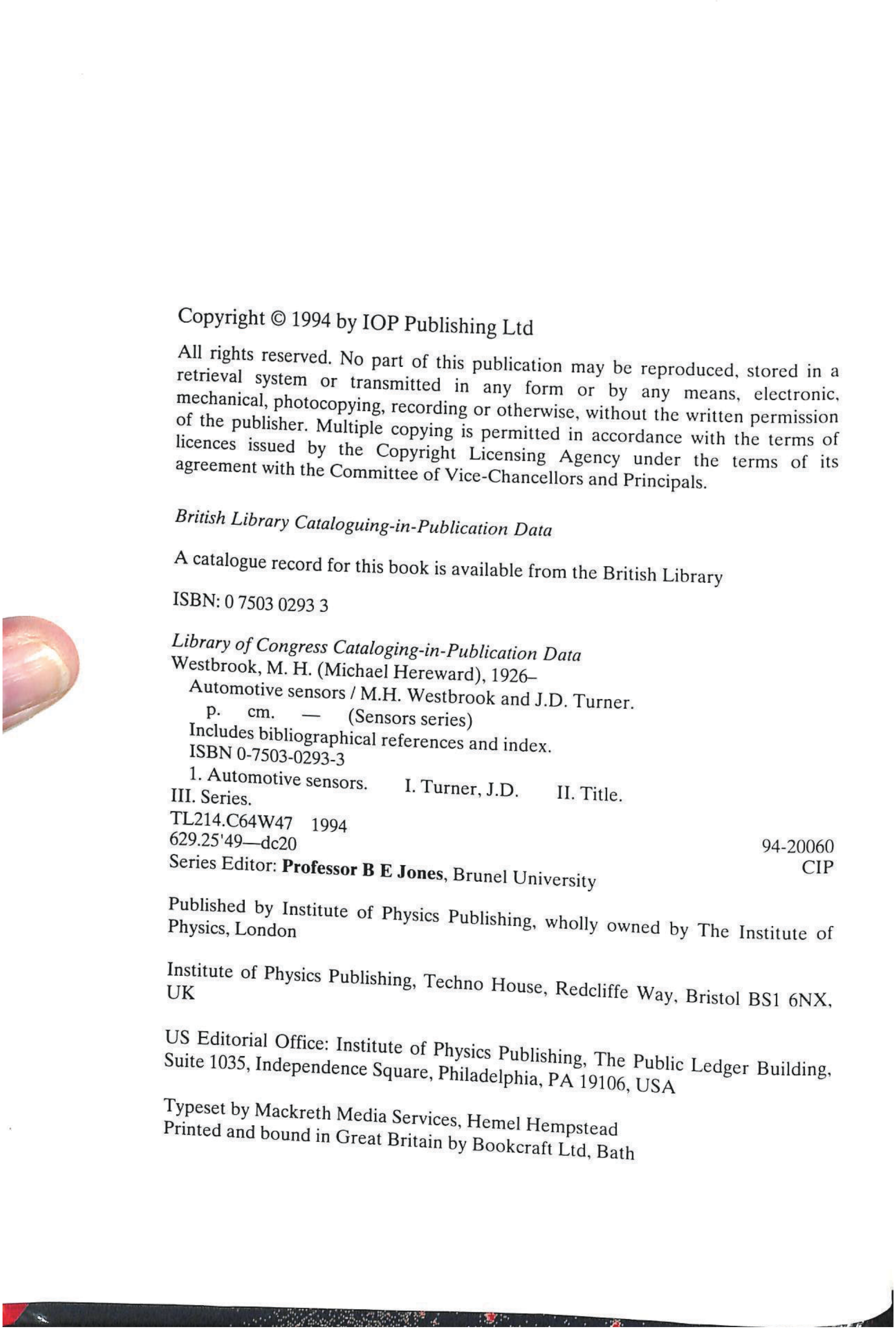

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Contents

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Preface

The idea for this book was suggested to the authors after the 1989 Institute of Physics Sensors Conference, at which one of us had presented a paper on future developments in automotive sensors and their systems. The interest in the subject seemed high and it was certainly a critical matter for the automotive industry that low-cost, accurate sensors be developed, sensors which could be used in the mass-produced vehicles of the future with their sophisticated electronic controls on engine, transmission, suspension, braking, instrumentation and driver information systems.

Writing a book involves a significant commitment of time and effort on the part of the authors and it seemed to us important that the result should be easily accessible to a wide range of readers, both those with a general interest in the vitally important area of sensors for use in the motor vehicle as well as those involved as users, developers and researchers of automotive control systems and the sensors which make such systems practical.

We have attempted to describe in reasonable detail the whole range of sensors currently used in automotive control systems with details of their construction, operation, characteristics and method of use. We have also included a short history of vehicle sensor development since the early days of motoring, which highlights the rapidity of recent developments.

Future sensor technology is of special interest and we have made some predictions on this and how developments in conjunction with computer systems of increasing sophistication but reduced cost and size could lead paradoxically to simplified sensor and control systems with added protection against system failure and improved diagnostics.

Vehicle electronic controls would not be possible without effective, accurate, low-cost sensors, and it is with the hope of widening the understanding of these critical devices that this book has been written.

Finally, we should like to record our thanks to Daniela Hoffmann, without whose efforts the manuscript would never have reached completion.

Mike Westbrook
John Turner
November 1993

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Introduction

Instrumentation is a subject of fundamental importance to engineering, and it is an increasingly vital tool for automotive engineers and designers. Over the last few decades the number of automated features built into a motor vehicle has increased steadily. Sensors are essential in any automatic control system. In general, control of any automated process (such as management of the ignition timing or fuel injection in a car engine) is achieved in three stages. Sensors are used to acquire information about the process to be controlled, a microprocessor is used to decide what action should be taken, and finally actuators are required to bring about the changes required by the microprocessor. A familiar automotive example of this process is electronic engine management, in which the piston position is sensed, engine speed and load are measured, and the required ignition timing and fuel injection are determined by a microprocessor. The optimised ignition timing and fuel injection data can then be stored in a semiconductor memory as a look-up table.

The costs associated with these three stages have changed in a markedly different manner over the past 20 years. For actuators, such as the electric motors used in growing numbers by automotive designers, the price–performance ratio has improved by a factor of approximately ten. This has made possible the introduction of features such as motorised seat and mirror adjustment. For microprocessors and computing power in general the improvement is much more marked, and is estimated to be of the order of 1000. For the average sensor, however, the price–performance ratio has only improved by about a factor of three. Moreover, each kind of sensor requires its own specialised signal conditioning system, which makes the application of electronic instrumentation expensive. This lag in the progress of sensor technology hampers the process of automation and its application to motor vehicles, and it is this deficiency which is likely to be addressed within the next few years by the introduction of integrated silicon or hybrid sensors containing built-in intelligence. The implications for the automotive designer are considerable, and will probably lead to major changes in the way in which control systems are designed into a motor vehicle.

Electronic sensors have been used in road vehicles almost from their inception. The earliest sensors were essentially switches, used to measure the crankshaft position for ignition timing purposes. An early example was Lenoir’s gas engine of 1865, which used a rotary switch connecting batteries to a coil to generate the spark. Later internal combustion engines used a rigidly coupled magneto to sense the engine cycle position. In the 1920s the familiar distributor, contact-breaker and coil arrangement evolved which has persisted to the present. The cam and contact-breaker system combines the two functions of position sensing and current switching. There are always problems of wear and contact surface deterioration with such a system, and most vehicles now rely upon an electronic arrangement in which the functions of position sensing and current control have been separated, with non-contact sensing techniques being adopted.

The next form of sensor to be adopted was used for measurement of fuel level. In early vehicles the fuel tank was often placed behind the dashboard, allowing the engine to be gravity-fed. As long as the tank remained in this position mechanical sensing devices such as manometers could be used. However, the fuel tank was soon moved to its current position at the rear of the vehicle, and a pumped fuel supply adopted. This led to the introduction of electrical methods for measuring and displaying the fuel level.

Other automotive potentiometer applications followed later. In the late 1950s Bendix developed and patented their ‘electro-injector’ fuel injection system, in which the throttle position was sensed by a potentiometer. This was subsequently refined by Bosch to form the basis of the well known ‘D-Jetronic’ system, used extensively by Volkswagen and others in the 1960s.

Potentiometer sensors are now frequently used for sensing throttle and brake pedal position, steering wheel motion and suspension displacement, for automatic gearbox control, and for many other applications. Potentiometers are cheap and reasonably reliable for many applications, but suffer from the major disadvantage common to all devices which rely on a sliding contact, namely wear. While they may be adequate for, say, throttle position transduction, they may give rise to problems if used for applications such as shock absorber motion sensing. This is because a car body tends to remain close to one position relative to the wheels throughout a journey, while it undergoes large numbers of small excursions around the ‘mean’ position. This phenomenon is known as *dither*, and unless special precautions are taken it can cause parts of the potentiometer track to become badly worn or even destroyed locally. For this reason many manufacturers are beginning to consider alternative, non-contact forms of displacement sensor, such as inductive, magnetic, capacitive or optical types.

The need to know the speed of the vehicle arose at an early stage, and speedometers became mandatory with the introduction of speed limits in the 1920s. The method chosen was to sense the speed of a rotating magnet driven from the gearbox, by means of the drag effect of eddy currents induced in an aluminium or copper ‘cup’ enclosing the magnet and working against a spring. This arrangement has survived almost unchanged for 70 years, and it is only recently that electronic systems have begun to appear in which a variable reluctance or Hall sensor is used to measure rotation rate by means of a toothed wheel.

Until the 1980s oil pressure was measured mechanically by a pressure pipe connection passed from the oil pump to the back of the dashboard. This arrangement has an unfortunate propensity to leak, which not only endangers the engine but is also injurious to the driver’s trousers, as both authors can testify! This measurement is now often made by micro-machined silicon or thick-film pressure transducers. Oil pressure is not usually displayed nowadays since modern bearings are very reliable. Lubricant pressure measurements in modern vehicles are normally used simply to illuminate a dashboard warning in the event of catastrophic oil loss.

A complex electromechanical system such as a motor vehicle has to be controlled by the operator in an environment which is constantly changing, and which can generate an almost unlimited amount of input data. To successfully control a vehicle in traffic as many as possible of the mechanical functions of the vehicle need to be automated, leaving the driver free to determine the vehicle’s speed and direction. The need for reliable, low-cost instrumentation in a vehicle is consequently very great. The critical quantities which have to be measured for powertrain control are ignition timing, airflow into the engine, throttle position and transmission speed, although useful supplementary information can also be gained from measurement of other quantities such as torque.

As noted above, early ignition control systems used mechanical sensing devices to control spark plug firing. Inlet manifold vacuum pressure is also measured in a mechanical system and used to infer engine load. The manifold pressure changes are used to mechanically alter the time at which a switch is closed to create the spark.

Modern timing sensors use electromagnetic, Hall effect or optical approaches to detect the motion of a projection attached to a shaft geared to the crankshaft. A certain amount of error is inevitable in these systems due to vibration and torsion (wind-up) in the geared drive. It is likely that in the future this will be eliminated by making timing measurements directly on the crankshaft. Engine load is then derived from a pressure sensor measuring inlet manifold vacuum.

Once engine load and speed have been measured the required ignition timing can be determined from a three-dimensional table relating load and speed to ignition advance. This function is implemented in a rather crude

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manner by the mechanical techniques described above, but in modern vehicles the optimised data is stored in a microprocessor memory in the form of a look-up table.

The use of a three-dimensional look-up table as a means of optimising engine operation has been extended by the introduction of electronically controlled fuel injection systems. Solenoid-actuated fuel injectors are again controlled by a microprocessor, with variations in the injector opening time being used to control the amount of fuel delivered to the engine. With this system both the quantity of fuel injected and the air mass flowrate into the engine are critical. Information on airflow can be derived by measuring inlet manifold vacuum with a pressure sensor, measuring air temperature and calculating the engine swept volume per unit time. This method is known as 'speed density' measurement and has been used for some years in US and Japanese cars. A direct measurement of the airflow into the engine is, however, now preferred, and was first accomplished by the Bosch air vanemeter. This transducer was the first into service and is still widely used. It consists of a spring-loaded flap which is placed in the airstream. The flap angle is related to mass-flow rate and is transduced by a potentiometer.

An alternative form of airflow sensor which is becoming widely used is the hot-wire anemometer. Automotive versions of these were also first developed by Bosch. They have the advantage of containing no moving parts, giving increased reliability, but require correction for changes in air temperature and can be susceptible to contamination of the hot-wire surface. Further development by Hitachi, discussed in chapter 4, has produced improved, robust devices which are now in full production use.

Increasingly stringent restrictions are being placed on the amounts of polluting gas which a car exhaust can emit. To reduce these so-called exhaust emissions two approaches are adopted: first, the air–fuel ratio entering the engine is controlled to ensure complete combustion. The air–fuel ratio is inferred from measurements of the amount of oxygen in the exhaust. Secondly, a three-way catalytic converter is placed in the exhaust to remove the critical pollutants of carbon monoxide (CO), unburnt hydrocarbons (HC), and nitrogen oxides (NO_x).

Exhaust gas oxygen (EGO) sensors make use of the fact that the migration of oxygen ions across a membrane separating two gases is a function of the partial pressure of oxygen in the two gases. At the stoichiometric air–fuel ratio (when sufficient oxygen is present to burn all the fuel) the partial pressure of oxygen in the exhaust gases equals that of the atmosphere. If suitable electrodes are placed on either side of the barrier a voltage output appears only when the air–fuel ratio departs from stoichiometry.

In the future, research will undoubtedly be directed towards improving the sensors and measurement systems described in this book. The move towards silicon will also continue, with micromachining and thick-film hybrid techniques being used to create transducer architectures on a very small scale.

The development of 'smart' sensors (in which much of the signal conditioning is carried out within the transducer housing) will provide standardised digital outputs, which are likely to be transmitted via a communications bus to the central control system. 'Smart' sensors will probably linearise their own outputs, compensate for environmental changes and include self-calibration and diagnostic functions both for themselves and for the systems to which they are applied.

Unfortunately, without special and expensive packaging silicon devices cannot cope with the highest temperatures found on a vehicle, especially around the engine, so the use of alternative semiconductor materials seems likely. One suitable candidate may be gallium arsenide, which is currently the subject of much research.

In general, an instrumentation system may be considered as falling into one of two categories. First, there are the laboratory or experimental measurement techniques used for research and development. This classification includes the instruments used to study the performance of an engineering prototype, and the laboratory devices used where high precision is required. The most important consideration faced by the designer of a measurement system intended for experimental work is its performance. In acquiring research data a high degree of repeatability, accuracy, linearity and reliability are required. The cost of this kind of system is usually of secondary importance.

The second sort of measurement system is that which forms part of a well understood device, usually a commercial product. Examples of this kind of instrument can be seen in any motor vehicle. The driver is provided with a speedometer to help control the vehicle speed, a petrol gauge to indicate when fuel is required and a milometer or other indicator to show when maintenance is needed.

For a well understood system such as a motor vehicle, a lower degree of instrument performance than that required for research is usually sufficient. For example, the accuracy of the average automotive speedometer is within a standard of −0% to +10%. However, this lack of resolution is entirely adequate to control the vehicle speed. In general the instrumentation supplied as part of a mass-produced device is of poorer quality than that used for experimental work. The principal reason for this is so that the complete system can be produced at an economic cost.

The aim of this book is to review the current state of automotive instrumentation, and to try and indicate where possible the likely course of future progress. The coverage is not restricted solely to sensors for volume application, although these predominate, but also includes a number of devices (such as torque transducers) which are at present restricted to use in development laboratories because of their cost. The reasons for thus extending the scope of this book are twofold: first, it is primarily intended for use by those engaged in or having an interest in automotive development, and secondly, because historically the trend is for today's laboratory tool to become tomorrow's consumer electronics.

1

The Evolution of Automotive Sensors

1.1 SENSORS IN VEHICLES BEFORE THE AGE OF ELECTRONICS

Sensors have been used in vehicles since the earliest days, certainly since the time when the electric spark came to be used as the preferred method for igniting the fuel–air mixture in the cylinder of the early Otto-cycle piston engines in the late nineteenth century.

The sensing in that case was of the position of the engine cycle via the magneto drive shaft, and developed through the distributor/contact-breaker/coil of later Otto-cycle piston engines to the familiar cam and contact-breaker which has dominated ignition timing control for 60 years from the 1920s to the 1980s.

The cam and contact-breaker combined both sensing of engine cycle position and control of the charge current into the coil; in spite of problems with wear and contact surface deterioration, it was only superseded in the 1980s by electronic sensing methods and the separation from that sensing of the current control function.

Another sensor which appeared fairly early in the evolution of the car was the fuel level sensor. The use of a rod to check the amount of fuel remaining was fairly rapidly replaced by manometer tube devices which remained usable for as long as the fuel tank was under the bonnet just in front of the windscreen, but as soon as pumped fuel feed replaced gravity feed to the engine, the tank was moved to its present position at the rear and it became necessary to use electrical means for measuring fuel level and indicating it to the driver. This led to the birth of the float and potentiometer sensor with either a current sensing display device using a bimetallic device to move the needle or a balanced electromagnetic instrument display. The float and potentiometer sensor is still with us, although its accuracy leaves much to be desired in the present situation of shallow tanks of complex shape. Development has concentrated mainly on producing potentiometer tracks of variable resistance with deflection which is matched in the fuel tank characteristic. However, new methods are now becoming available and will be discussed in detail in chapter 11; but because the float and potentiometer is such a low-cost device it is

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difficult to find a more accurate sensor for a similar price.

The need to know the speed of the vehicle existed as soon as the person with the red flag was sent packing, and eventually became legally required when speed limits were introduced in the 1920s. The method chosen was to sense the speed of a rotating magnet driven through a Bowden cable from the rear of the gearbox, by means of the drag effect of the eddy currents induced in a non-ferrous 'cup' enclosing the rotating magnet and connected to a sprung pointer calibrated in miles per hour. This device has survived for 70 years, and it was only during the 1980s that the Bowden cable was increasingly removed and replaced by an electromagnetic sensor on the gearbox producing electrical pulses at a rate directly related to speed, this output then being used as the input to an integrating electromagnetic speedometer display instrument.

Oil pressure level, particularly important in the days of somewhat less reliable bearings than today, was also sensed and displayed normally by a direct pressure pipe connection from the oil pump supply line to a Bourdon tube gauge giving a direct pointer indication as the tube deflected. In some cases even simpler devices were used, such as a sprung cylinder sealed into the end of the pressure pipe which protruded further from the dashboard as the oil pressure rose. It had an unfortunate propensity for leaking and dripping oil on the knee of the driver, as the authors can verify from personal experience!

Engine temperature measurement was also included, although only on the more expensive cars. The method used for this was a bulb thermocouple screwed into the engine block giving a voltage signal to a sensitive electromagnetic pointer instrument; the ubiquitous and robust thermistor has long displaced this rather delicate device.

The devices described here were the only sensors used on cars from the 1920s through to the 1960s, and it was not until the advent of electronic controls that this situation changed.

1.2 THE ADVENT OF ELECTRONIC CONTROLS

The performance of high-speed car engines had always been limited by the loss of spark energy in the ignition system at high engine speeds, owing to the limited time available to charge the coil in the short contact period available with the cam/contact-breaker ignition system. The system also suffered from a relatively short life and a continuing deterioration in timing accuracy owing to wear between the cam and cam follower on the one hand, and the build up of the deposits of arcing on the contact surfaces on the other. In fact, if these two effects had not been in opposite

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directions and partially cancelled each other out the deterioration in performance with time in use would have been much more rapid than in fact it was.

It was realised during the late 1950s that if the coil could be controllably charged using a power transistor (and suitable power transistors were then becoming available), and triggered by a non-contact inductive or photoelectric sensor which had purely a timing function rather than the timing and current switching function of the contact-breaker, then the system would operate without these major disadvantages. So 'breakerless' electronic ignition was born and first used successfully in some of the racing and rally cars of the 1960s. This new ignition system was not, however, adopted for many years for mass-produced cars for a reason that is critical when any application of new technology is considered for the motor vehicle; it cost significantly more than the contact-breaker system it replaced.

So, electronic breakerless ignition was in existence as an available improvement but was not adopted outside the specialist car market until the increasing environmental pressures in the USA and, in particular, in California, on the 'smog' issue forced an agonising appraisal of what could be done to reduce the levels of carbon monoxide (CO) and the hydrocarbons (HC) emitted from the exhaust of US vehicles, ready for the first introduction of emission control regulations in California in 1966.

One of the actions quickly established was that better control of ignition timing had an important part to play in making an improvement, and that that improvement could be maintained throughout the life of the car, and certainly over the required 40 000 mile test distance, if breakerless ignition was used. It was also shown that the accurate control of the timing advance characteristic of the ignition system, which relates engine speed and load (represented by the manifold vacuum pressure level) to ignition advance angle, was critical in obtaining the lowest emission levels.

This initial introduction of electronics to ignition control triggered much more detailed studies of how engine performance, particularly in respect of exhaust emissions, could be improved by the use of electronics, and resulted in the development of electronic fuel injection in the USA, Germany and the UK. By 1967 Bosch and Lucas were in production with fuel control systems for Europe designed primarily to improve performance rather than reduce emissions. In the USA, however, in spite of the early work by Bendix, electronic fuel control was not introduced in production cars until 1975, when the increasing severity of the exhaust emission regulations made the use of catalysts in the exhaust system necessary and with this the need for precise electronic methods of controlling fuelling unavoidable. So, electronic ignition and electronic fuel injection became established very widely in the USA in the late 1970s as the only effective method, in combination with exhaust emission regulations (which by then had added the oxides of nitrogen (NO_x) to the hydrocarbon (HC) and carbon monoxide (CO) emissions previously controlled).

1.3 STAND-ALONE AND INTEGRATED SYSTEMS

Initially separate ignition and fuelling control systems were used, but it quickly became obvious that since the same control parameters of inlet manifold pressure and engine speed were required to determine the engine operating condition, and the consequent ignition timing or fuel quantity, that these stand-alone systems could be combined to use the same sensors and to operate interactively. The subsequent addition of direct-inlet manifold mass air flow measurement instead of its derivation from the measurement of inlet manifold pressure and swept cylinder volume, did not change the move towards integrated engine control systems.

More recently, stand-alone systems for anti-lock braking control have been developed to provide the complementary facility of anti-spin control, and this has usually involved the communication of signals to the engine control system to reduce engine power output when wheel spin occurs as well as braking the offending wheel. So the communication of sensor and control signals between systems which were originally stand-alone has progressed on a rather *ad hoc* basis up to the present.

However, the advent of in-vehicle data links or multiplex systems — initially considered because of their ability to simplify increasingly complex wiring looms — offers the capability of providing sensor signals around the vehicle, and in some cases where the control time delay is acceptable, direct control signals.

This brings the possibility of fully integrated control systems much nearer and increases the need for sensors with signal processing capability built in (smart sensors), and the ability to be connected directly to an in-vehicle data link.

1.4 SMART SENSORS

The decision on how much intelligence to add to a sensor is a difficult one; as also is the definition of a 'smart' sensor. Simple impedance conversion to enable, for example, the high-impedance signal from a piezoelectric sensor to be fed down a line to its associated electronic control unit, would certainly not qualify; but when sensors are produced with electronics which permit diagnostics, linearisation or even self-calibration, then this certainly falls within the definition. It is even more appropriate when the electronics added standardises the output, converts it to a digital data-bus format, or adds a capability to process and respond to incoming interrogation signals on the data bus.

The theme of the 1990s in automotive sensor development seems certain to move increasingly towards the world of integrated systems, where instead of being a 'stand-alone' device providing a specified output to an electronic control unit, the sensor becomes an integral part of the electronic control system, with the electronics associated specifically with processing its output and diagnosing its correct operation being found increasingly as an integral part of the sensor itself (the 'smart' sensor).

This smart sensor can be realised either by integrating the 'intelligence' onto the same chip used for the sensing function, or by using a thick- or thin-film circuit to mount a separate 'smart' circuit within the housing of the sensor. This approach is compatible with the linking of electronic systems in the vehicle by means of a data link or multiplex wiring system, since the coding and decoding functions required for such a system can, potentially, also be included in the 'intelligent' part of the sensor, so giving a compact device capable of providing standardised coded information to any electronic control unit. The control unit is then simplified because it does not now have to carry all the electronics and entry ports required for the analogue/digital conversion of a large number of sensor inputs.

The second long-term development seems likely to be the advent of smart sensors with the capability of self-calibration. Here we may expect to see low-cost smart sensors with relatively poor linearity but high repeatability being initially cycled under carefully controlled conditions through their full operating cycle, ideally *in situ* in the vehicle. The increment in sensor output per unit change of the measurand then represents the calibration of the sensor. This information is then stored in the smart sensor's memory where it can be used as the calibration curve against which future operational measurements are made. Providing the sensor has good repeatability, then wide variations in linearity and range between nominally similar sensors can be accepted, giving the opportunity for the increasing use of low-cost devices.

The third longer-term development which is likely to further change automotive control systems and the way in which sensors are used is what we call 'embedded simulation' (this will be discussed more fully in chapter 14).

The development of computer simulation of vehicle systems such as the engine, transmission, suspension etc, is currently proceeding apace, and further developments involve combining those simulations to make it possible to represent the complete vehicle. Currently, this requires substantial computing power and memory, but it seems certain that by the turn of the century computing power of this order will be available in low-cost/small-package devices. At this point it seems probable that control systems for vehicles (and probably other self-contained real-time control systems in industry and around the home) will change in character, so that a full simulation of the system being controlled is embedded in the control system.

With the availability of this simulation it will be possible to compare the actual performance of the vehicle, as measured by suitable sensors, with the ideal as specified by the embedded simulation. This not only provides the opportunity for comprehensive adaptive feedback control of all controllable functions, but also provides a target against which the performance of all these functions can be compared, hence making full active diagnostics possible.

Another benefit of such a system is the ability to continue operating the vehicle satisfactorily even when failure of major parts of the main control system, in particular sensors, occurs. In fact, one benefit might well be the ability to dispense with many of the existing sensors, since, given information on, for example, only engine speed, torque and temperature, the simulation — particularly if it is designed to be adaptive — may well be able to specify the full operating conditions of the engine. Then, as major, slowly varying conditions such as wear, fuelling or altitude of operation change, the simulation is suitably modified to take this into account.

These three areas, integrated smart sensors, smart self-calibrating sensors and embedded simulation, seem certain to cause major changes in control systems and their associated sensors and need to be borne in mind when looking at new or improved sensor technologies for future application.